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Geothermal Energy Projects Planning and Management

Edited by
Louis J. Goodman
Ralph N. Love

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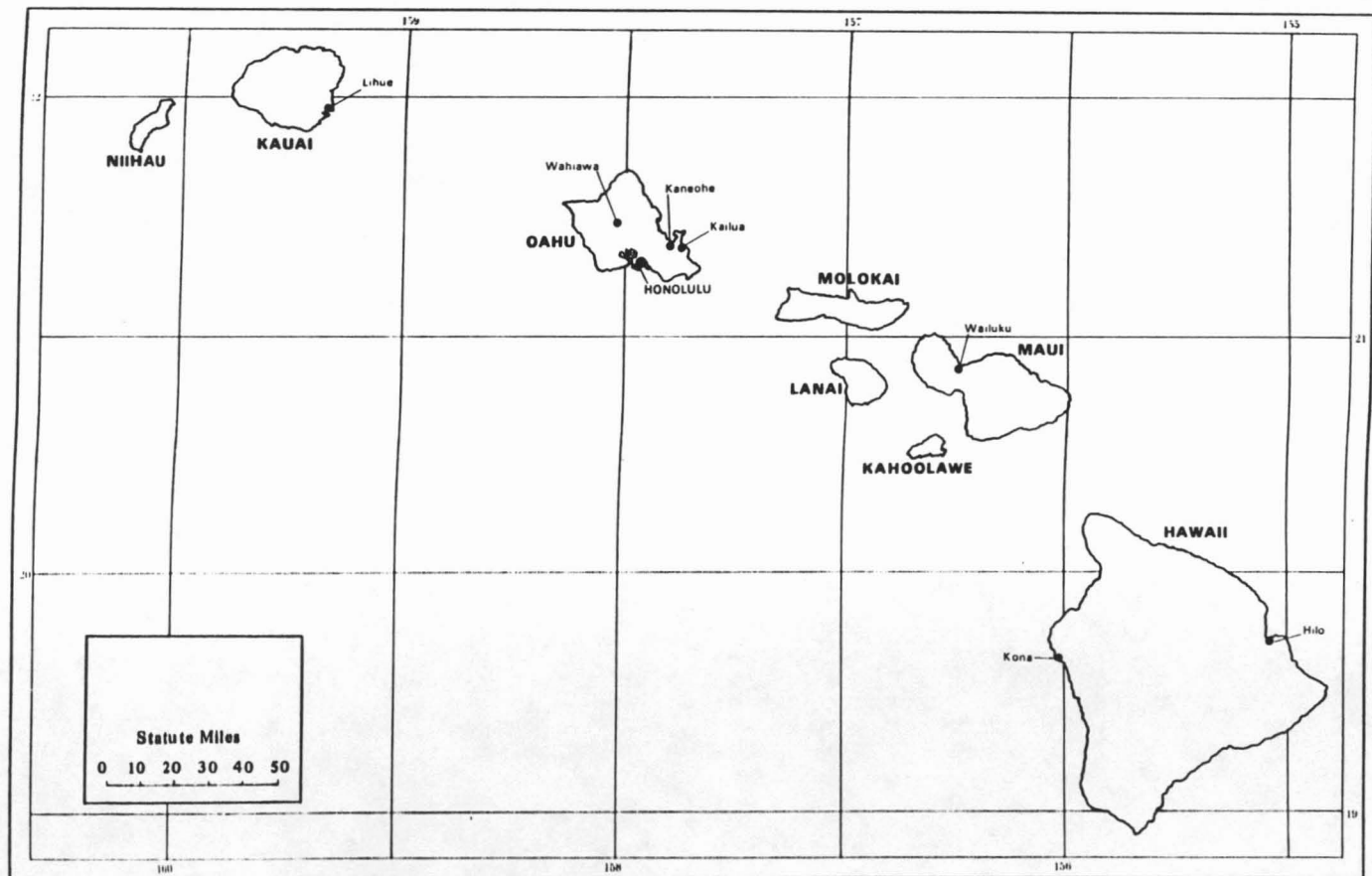
Hawaii Geothermal Project: United States

Louis J. Goodman
Tetsuo Miyabara
Barbara Yount

PROJECT BACKGROUND

Hawaii, one of the 50 states of the United States, is an island chain located in the central Pacific Ocean, approximately 2,500 miles (4,000 kilometers) west of the continental United States. It is composed of numerous islands extending across 2,000 miles (3,218 kilometers) of the Pacific and is dominated by five major islands (see fig. 3.1). At the northern end of the chain lies the capital and population center of the state, the island of Oahu. Oahu has a population of 718,400, while the state of Hawaii as a whole has a total population of 886,400. Approximately 200 miles (320 kilometers) south of Oahu is the island of Hawaii, which is the youngest and the only volcanically active of the major islands. It has a population of 76,400.

The state as a whole is blessed with magnificent mountains, beautiful beaches, cool valleys, lush vegetation, fertile plains, abundant sunshine, and plentiful rainfall, all of which have made it possible to develop both a thriving tourist industry and a profitable agro-industry in sugar and pineapple. Ironically, the same geography and geologic characteristics that have helped these industries to thrive have also deprived Hawaii of the conventional sources of fuel needed to power them. Because of the islands' recent volcanic origin, no indigenous fossil fuel reserves exist. In addition, geography has isolated Hawaii from potential energy sources. Unlike the rest of the United States, no coal comes into the state by rail, no natural gas is received by pipeline, and no regional grid of electricity serves Hawaii. The only presently feasible source of fuel is oil, shipped in by large tankers. In short, Hawaii is almost totally dependent upon outside shipments of oil, and is thus vulnerable both to disruptions in delivery and to fluctuations in the global market. The overall vulnerability was succinctly summarized by the opening statement from the Mayor's Energy Resources Committee: "In Hawaii, 'Energy is Oil.' We are totally dependent on oil and gas for our energy consumption needs."(1)



This vulnerability is underscored by several statistics. From 1960 to 1974, over 99 percent of Hawaii's power was generated from crude oil which was shipped into the state.(2) Approximately 25 percent of all petroleum products was used to generate electricity, 25 percent was used for air transportation, 28 percent was used by gasoline service stations, 14 percent was used for industrial and commercial purposes, and 8 percent was used for a variety of other purposes.(3) Several trends have also increased Hawaii's vulnerability. The cost of oil has risen dramatically; in 1970 it was US\$2.50 a barrel and by 1974 it was US\$10 a barrel. Between 1958 and 1975 consumption of petroleum rose 300 percent, from 12 million to about 38 million barrels per year.(4)

Yet this dependence and vulnerability upon imported oil is a paradox because Hawaii possesses abundant alternative energy sources – solar, wind, wave, biomass, ocean thermal, and geothermal. Unfortunately, these sources, until recently, have not been developed. A significant factor in this lack of development was the lack of an overall United States energy policy. In its absence, the responsibility for developing alternative energy sources fell both to the individual private utility companies, which generate most of the power in the United States, and to the individual state and county governments. For the utility companies, however, there was little incentive to risk their capital in research and development. Fossil fuel sources, particularly oil, were abundantly cheap, and therefore cost-effective; nonconventional power sources could not compete with oil. Thus, the initiative for developing energy alternatives was left primarily to state and local organizations, such as universities and planning boards. For the most part, these organizations did not have the resources to conduct the research and development necessary to make feasible the various energy alternatives. Nor did they receive necessary support from the state governments, since energy development was not seen as a high priority.

In contrast, the government of the state of Hawaii and the county governments of each island placed a high priority on the development of energy alternatives. Hawaii's vulnerability to oil shortages and dependence on oil had made state and county officials keenly aware of the urgency to develop Hawaii's indigenous sources of energy. As early as 1970, three years prior to the Arab oil embargo, the Hawaii State Legislature passed a resolution requesting the University of Hawaii's Center for Engineering Research to submit a study on the potential of new energy sources for Hawaii. The report was completed in 1971 and it listed a number of alternatives.(5)

Geothermal energy was considered one of the more exciting new possibilities. The concept itself – that of using the heat of the earth to generate electricity – could be applied in Hawaii by harnessing and controlling the sometimes destructive heat of the volcanoes. Since the island of Hawaii was formed by the largest volcanic mass in the world (see fig. 3.2), geothermal energy had great potential. And this potential captured the imagination of many of the state legislators and helped gain local momentum for geothermal research.

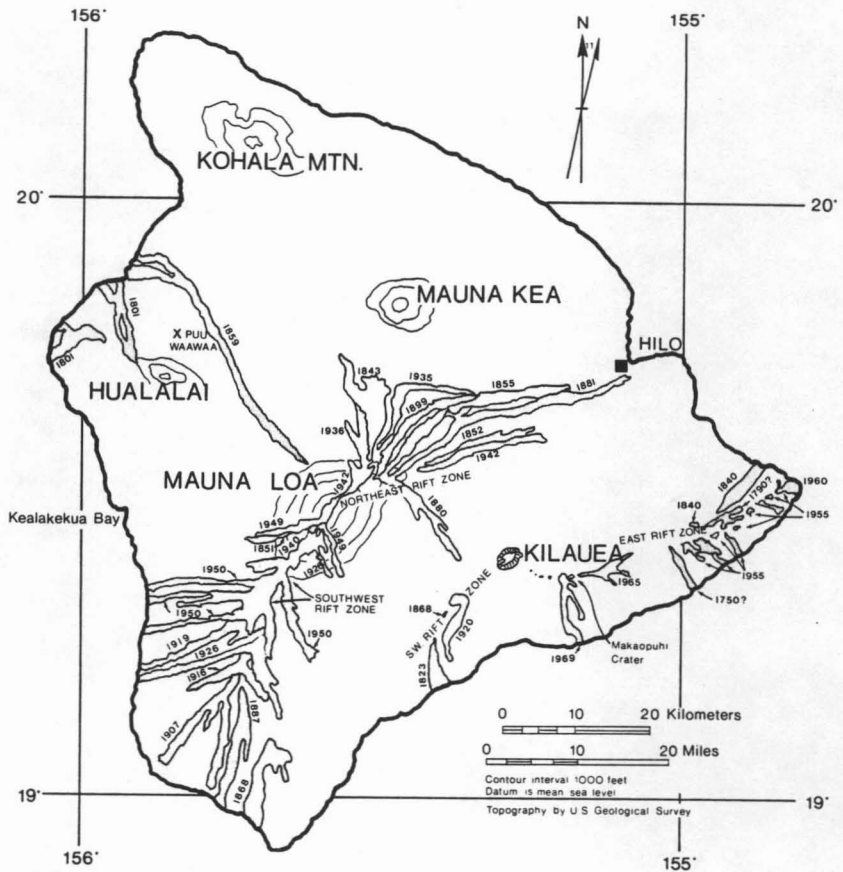


Fig. 3.2. The island of Hawaii with volcanoes.

Additionally, the county government of the island of Hawaii was enthusiastic to make use of its untapped resource. In this regard, several early experiments had been conducted on the island. In the 1920s someone had attempted to use the volcanic heat directly to generate electricity. More recently, in the 1960s explorations for geothermal reservoirs had been conducted. These explorations resulted in the drilling of four wells in the Puna region, the deepest of which was about 700 feet (213 meters). However, no reservoirs were found and the drilling projects were abandoned as economically unfeasible. If any reservoirs existed, they existed at considerably greater depths and could be exploited only at great cost.

PHASE I: PLANNING, APPRAISAL, AND DESIGN

Identification

In 1972, with the encouragement of state and county governments, Howard Harrenstein, the director of the University of Hawaii's Center for Engineering Research and a long-time believer in Hawaii's geothermal potential, submitted a US\$2.7 million research proposal to the National Science Foundation (NSF). The proposal outlined a two-year project, called "Project Pele." It was essentially a multidisciplinary effort that would include:

1. Geophysical program: geophysical explorations on the island of Hawaii; these would include surface studies, as well as the test drilling of a series of shallow wells and a deep well, possibly to depths of 10,000 feet (3,048 meters);
2. Engineering program: engineering research into problems associated with geothermal generation of electricity; and
3. Environmental/socioeconomic program: investigations on geothermal energy's socioeconomic and environmental implications.

The project appeared to have one major drawback: although it outlined a very ambitious plan that would result in potentially useful scientific information, it was a pure research project. No plans were made to actually convert geothermal energy into electricity. Nonetheless, the Hawaii State Legislature and the county government of the island of Hawaii strongly supported the proposal, each granting the project \$100,000 contingent upon its receiving NSF matching funds. However, the project was not immediately funded.

Instead, in June 1972, NSF awarded a smaller geothermal research grant of about \$400,000 to George Keller, a professor of geophysics at the Colorado School of Mines. Keller intended to drill a well about 3,500 feet (1,067 meters) deep in the Hawaii Volcanoes National Park, at a site where the United States Geological Survey indicated there might be underground steam. Even if Keller discovered no reservoir of steam, he would take core samples and conduct geophysical tests. Since these tests would indicate the potential of usable geothermal energy in Hawaii, they would have a strong bearing on the more elaborate Project Pele proposed by Harrenstein. Positive findings would add justification for funding the multimillion dollar research project.

Keller's project was eventually successful in obtaining research data and in drilling to its target depth of 3,500 feet (1,067 meters). The project also encountered certain problems.

One significant problem arose just prior to the drilling. The Congress of Hawaiian People, a group representing the interests of native Hawaiians, asked Hawaii Volcanoes National Park officials to delay the project. A co-chairman of the congress said his group had two objections. First, the drilling might violate religious and spiritual beliefs of the Hawaiian people. He stated that "Hawaiians should have

been consulted before the drilling was approved because it will take place on the sacred religious grounds of our ancestors."(6) He argued that Keller should have prepared an environmental impact statement that detailed the site's religious and historical value. Second, he claimed that if the drilling found any commercially usable steam, Hawaiians should profit from it because the state constitution declared that indigenous natural resources should be used for the betterment of the native Hawaiian peoples.

Both objections were eventually resolved. Keller met with the congress and ensured them that the specific project site was not in an area of historical or religious significance. He also obtained a ruling from the Hawaii Volcanoes National Park superintendent stating that any geothermal steam from the site would never be exploited commercially. The park was a public reservation and therefore none of its resources could be bought or sold.

Formulation: The Initial Proposal

While Keller's project was taking place, the proposed Project Pele suffered a setback when Harrenstein resigned his University of Hawaii post to accept another position at the University of Miami. Since Harrenstein was listed as the project's principal investigator, the proposal had to be revised and then resubmitted to NSF. Initial planning meetings were held and the first decision made was to name a management team to replace Harrenstein. The management team was to consist of John Shupe, dean of the University of Hawaii's College of Engineering, George Woollard, director of the University of Hawaii's Institute of Geophysics, and John Craven, the state of Hawaii marine affairs coordinator and the dean of the University's marine program. The project was also renamed the Hawaii Geothermal Project (HGP).

In August 1972, an NSF official advised the HGP management team that a single person should be assigned to manage the project. The failure to name one well-qualified person to assume overall leadership would endanger potential funding. It was then decided to appoint John Shupe as the principal investigator. He would be the project director, responsible for the project's overall administration and management and, in essence, responsible for the degree of project success or failure. Sharing responsibility with him were to be three co-principal investigators: Augustine Furumoto, a professor of geophysics at the University of Hawaii; Paul Yuen, associate dean and professor of the University of Hawaii College of Engineering; and Robert Kamins, a professor of economics at the University. They were to be the coordinators of the geophysics program, the engineering program, and the environmental/socioeconomic program, respectively. Each would devote half his working time to the project and the rest to his normal university duties.

An HGP executive committee was also established. The executive committee was composed of Shupe, the coordinators of each research

program, George Woollard, and John Craven. Although this committee would make no direct decisions, it would play a policy making and planning role. Figure 3.3 illustrates the 1972 organizational chart of HGP.

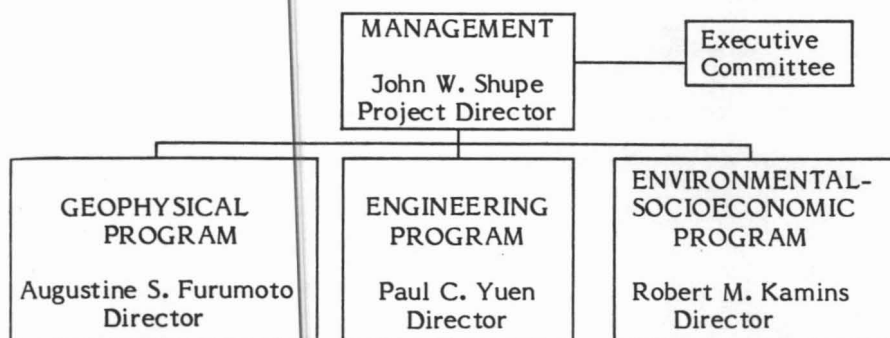


Fig. 3.3. Hawaii Geothermal Project – organizational chart, 1972.

By late 1972, the executive committee realized that the proposed project would have a better chance of being funded if it included research and development that led directly to the conversion of geothermal energy into electricity. This would demonstrate the practical value of the research, as well as provide some tangible results for such costly research.

Consequently, the HGP executive committee expanded the scope of the project to include the planning and construction of a 10-MW prototype geothermal power plant. Like the originally proposed Project Pele, research under GHP was divided into three areas: geophysics, engineering, and environmental/socioeconomic. A total of 37 separate tasks were identified in these three areas (see fig. 3.4) and a team of 54 researchers was named to conduct the investigations.

Requiring US\$5 million over a two-year period, the HGP proposal was conceived of in the following three stages:

Stage I was to be the initial, short-range exploratory and applied technology research that would assist in the early development of geothermal power. This stage was intended to acquire scientific information and to help locate possible drill sites for geothermal steam.

During Stage II, the geophysical data collected in the first stage would be used to establish an exploratory drilling program. This stage would culminate in drilling one deep hole that would hopefully tap a steam or hot water reservoir.

Stage III was envisioned as a planning stage for the actual construction of a geothermal power plant. The well would be analyzed and the tests necessary to design the power plant would be conducted. The

Geophysical Surveys

Photogeologic survey
 Aeromagnetic survey
 Electrical resistivity survey
 Electromagnetic induction survey
 Microseismic survey
 Offshore seismology
 Thermal (300-feet) survey
 Shallow seismic survey
 Petrology, structural, geology
 and geochemistry
 Geochemistry of fluids
 Physical properties of rock
 Ground water
 Deep drill
 Model study
 Evaluation

Engineering Studies

Well test analyses
 Ghyben-Herzberg lens dynamics
 Geothermal plant optimum design
 Corrosion and wear reduction
 Electrical energy transmission
 Energy extraction from high-
 temperature brine
 Materials for use with magma and
 hot rock
 Direct extraction of magma energy
 Direct energy conversion
 Alternate modes of energy
 transmission and storage
 Pilot plant steam production
 Mechanical design and layout for
 pilot plant
 Pilot plant electrical generation
 and transmission

Environmental Socioeconomic Studies

Environmental impact
 Geotoxicology of thermal areas
 Land use and land law
 Legislation and regulation
 Planning
 Economic analysis
 Phytoplankton by-product
 research
 Agriculture research
 Trace-metal recovery

Fig. 3.4. Hawaii Geothermal Project – proposed research.

Source: Hawaii Geothermal Project Quarterly Progress Report No. 1, June 1, 1973 through August 31, 1973, pp. 1-3.

actual generator design would then be drawn up. In May 1973, approximately a year after the submission of the project proposal, NSF announced that it was awarding the Hawaii Geothermal Project (HGP) a one-year budget of \$252,000. Although other geothermal projects from around the United States had requested funding, it had been decided that a high national priority was to obtain more information on geothermal potential in island volcanic regions. This amount, added to the initial grant of \$200,000 which had been given to the project in 1972 by the state and county governments, provided HGP with a first-year budget of \$452,000. Although the budget was far less than the originally requested five million dollars, it was viewed as the beginning of a long-term commitment to develop geothermal power in Hawaii. The budget was also sufficient to enable Stage I, the early exploratory research, to get underway.

Feasibility and Appraisal: 1973-1975

The initial research activities of HGP were, in a sense, the formal feasibility studies, determining the chances of the project to eventually generate electricity from Hawaiian geothermal sources. The exploratory geophysical surveys would help determine if and where reservoirs of steam or hot water existed and thus allow NSF to assess HGP's scientific feasibility. The engineering and environmental/socioeconomic studies would identify and clarify the technological, environmental, legal, regulatory, and economic problems that could hinder the eventual development of geothermal power in Hawaii - provided, of course, that a usable source of geothermal energy existed.

Overview of initial project activities

Upon word of NSF's allocation to HGP, the state government and the county government of Hawaii Island, which both strongly supported the development of alternative energy sources, released funds to HGP to begin planning activities. Shupe then convened a meeting of the executive committee and each of the program coordinators was given a separate budget. This would provide each coordinator with the independence and flexibility needed to administer the research in his area and, at the same time, make each accountable for his program. Shupe would be responsible for the overall management and coordination of the project. He would also be responsible for maintaining project cohesiveness and for ensuring that each research program developed consistently with overall project goals.

The executive committee also had to make important budgetary decisions. The separate budgets initially proposed by each program coordinator had to be reduced because the initial level of funding was considerably less than anticipated. Thus, it was decided that each program would receive only enough funds to initiate crucial tasks. The bulk of the money, however, would be allocated to the geophysics

program because it was conducting the exploratory surveys crucial to the project's continued progress. Despite the reduced funding, it was anticipated that NSF or some other government agency would provide HGP with additional funds if the geophysical surveys indicated the existence of a reservoir of steam.

With these decisions made, the directors of the geophysics, engineering, and environmental/socioeconomic programs began organizing their respective activities.

Geophysics program

The geophysics program director, Augustine Furumoto, had requested about \$800,000 for 1973-1974 activities, but received only about \$250,000. He decided to limit the geophysical surveys to those which could begin immediately; the remaining surveys depended upon the data from the initial surveys and would be undertaken if additional funds were received. The chosen surveys were those crucial in identifying a potential reservoir of steam or hot water. Providing clues about the subsurface conditions, they would be like pieces of a large jigsaw puzzle, which, when put together properly, would serve as a geophysical model of the volcanic area. These surveys included: 1) photogeologic, 2) geoelectrical, and 3) microseismic, and geochemical. Other surveys, such as the gravity and magnetic, were planned for 1974, if funds were available. The photogeological survey, contracted out to a commercial firm with both the necessary equipment and experience, involved flying over the volcanoes at approximately 2,100 feet (640 meters) and taking infrared photographs of the rift zones – zones of innumerable fissures that served as underground pathways for the rise of magma. When developed, the photographs would expose gradations of surface heat and would locate volcanic vents and other "hot spots" along the rifts. Any surface temperatures that exceeded the highest range of the film would be exposed as spots of white. Flights were conducted during August 1973 and the photos were developed soon afterwards. The photographs revealed a concentration of white dots along the east rift of Kilauea volcano, in an area named Puna. The temperature range indicated by the film was 61°F (16°C) to 77°F (25°C).

The initial electrical resistivity survey was subcontracted to George Keller, who already had equipment in the field from his earlier project. These surveys, called dipole-bipole mapping, checked the earth's electrical resistance by passing an electrical current between two poles set in the ground; low resistivities readings indicated conductive foundations, such as hot saline water or highly conductive soils. Since low resistivity readings could also indicate pipes or electrical wires, several surveys had to be conducted to help determine the true sources of the readings. The survey indicated two areas of low resistivity that could be attributed to thermal sources – the Opihikao anomaly and the Pahoa anomaly, both located in the area of Puna. The Opihikao anomaly had resistivities of about 5 ohms per meter (ohm/m) from 1,969 to 6,890 feet (600 to 2,100 meters), while, between the same depths, Pahoa had resistivities of about 8 ohm/m.

The microseismic surveys were to have measured the velocity at which sound passed through the ground, and thus provide indications about the area's subsurface structure. These surveys were postponed because of delays in receiving the necessary equipment. The geophysics coordinator agreed, however, to begin a ground noise survey, which would indicate the variance in subsurface noise. Since in Hawaii, sites of volcanic activity produce intense sound, these surveys would help locate sources of geothermal heat. Like the initial surveys, the ground noise survey discovered intense sound.

The geophysical surveys progressed steadily through early 1974, with the geophysics coordinator assigning tasks to appropriate geophysicists on the project team. Often, the assigned individual would subcontract a specially equipped commercial firm to conduct the survey, and then analyze the data himself. This arrangement proved satisfactory for many of the tasks. However, when no commercial firm could undertake the surveys, the geophysicist would have to order special equipment or redesign existing equipment, and then conduct the survey. This led to some delays and the surveys fell behind schedule.

Engineering program

The engineering program, like the other two research programs, had to reduce the number and scope of its initially proposed research tasks. The engineering director, Paul Yuen, thus decided to concentrate on: 1) geothermal reservoir engineering, and 2) optimal geothermal plant design. These two tasks dealt directly with applied research crucial to the production of geothermal energy in Hawaii.

Geothermal reservoir engineering was initially two separate tasks, but because of their close linkage, these were later collapsed into one task with two related components. These components included: 1) numerical modeling, and 2) well testing and analysis. The engineers working on numerical modeling attempted to computer-simulate the operational dynamics of a geothermal system under different conditions. To derive the mathematical relationships, they first had to investigate several issues. How, for example, would pumping, reinjecting, and recharging the geothermal well affect the Ghyben-Herzberg lens? The Ghyben-Herzberg lens is a pool of fresh water trapped in porous rocks beneath the island's surface. Sea water also permeated the island's subsurface, but the fresh water was lighter and thus floated on the sea water, forming a lens which supplied much of the island's water needs. When the engineers completed these investigations, they would construct a model that would generate computer answers to questions such as: How deep must the well be drilled to avoid destruction of the Ghyben-Herzberg lens? What is the life span of the well? What is the capacity of the geothermal reservoir?

Well testing and analysis would culminate in engineers and geologists going into the field to test measure the geothermal well - assuming, of course, that a successful well were drilled. The task would proceed in several stages. Initially, the engineering team would eval-

uate the existing equipment and the methods used by the geothermal engineers in the rest of the world; this involved a literature search. Then they would examine the techniques used by petroleum reservoir engineers to measure oil wells. However, since the volume and capacity of a geothermal reservoir depended on temperature, but a petroleum reservoir did not, many analytic techniques of petroleum reservoir engineering were inadequate. Thus, during the next stage of research, engineers would modify and adapt both the geothermal and the petroleum methods to develop a comprehensive geothermal testing program. The completed program would be appropriate for a geothermal well and would include a complete array of geological and reservoir engineering tests, as well as recommendations for the purchase of equipment. After the researchers developed the well testing program, they would conduct the tests on the well itself. Ultimately, the data collected would help predict the life span and capacity of the geothermal well.

The engineering program's second research task was to study power plant designs that could be used if a geothermal well were discovered. Since the optimal power plant design depended upon the form of energy produced by the well (it might be in the form of dry steam, wet steam, hot water, gases, dissolved solids, or vapor) the engineering team might have to study many options. The team decided, however, to limit their investigations to two basic types of geothermal power plants: the vapor flashing plant and the binary fluid plant.

The vapor flashing plant would be practical if the well produced geothermal steam. In this system, the geothermal well would contain hot water under intense pressure. As the water would rise from the bottom of the well, the pressure on it would decrease and some of it would flash to steam. The well would thus emit a mixture of hot water and steam. The steam would be separated from the hot water by a separator and piped directly to a turbine generator. The hot water could be discarded or could be piped to another separator, which would further reduce the atmospheric pressure on the water, thus causing it to flash to steam. This steam would then be piped to the generator (see fig. 3.5).

The binary fluid plant would be efficient if the well produced hot water. In this system, the hot water would be used to heat a secondary liquid, such as isobutane. When the isobutane became vaporized, it would power a turbine that would then produce electricity (see fig. 3.6).

To design the optimal plant, the engineers would have to answer questions such as: What would be the most efficient steam pressure to power different size plants? What plant configuration would be most feasible given different well conditions? What kind of turbine generator should be used if the well produced wet steam, dry steam? How should the plant's discharge system be designed to make it environmentally sound?

The engineering team began work on each of these tasks in late 1973, and the research proceeded smoothly through 1974. However, much of the research was intended to be applied to the actual

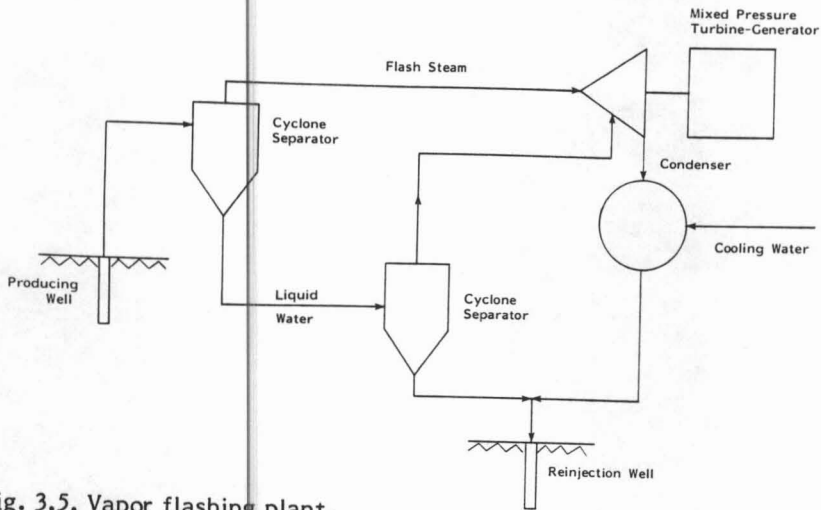


Fig. 3.5. Vapor flashing plant.

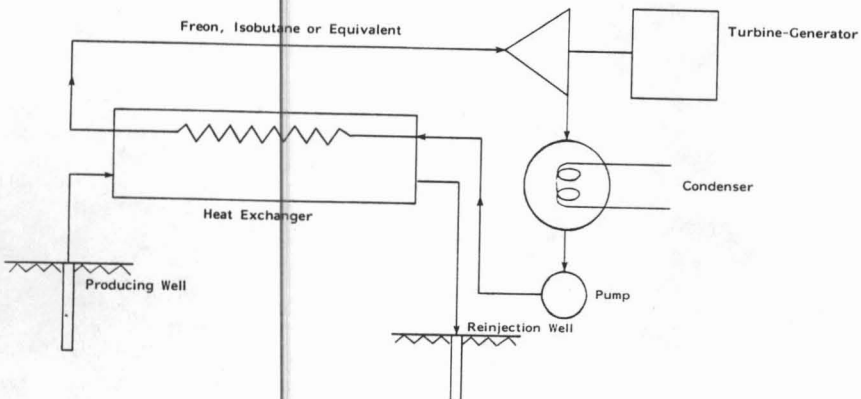


Fig. 3.6. Binary flashing plant.

production of geothermal energy in Hawaii. Thus the engineering program could be successful only if money were obtained to continue the overall project and only if a successful geothermal well were drilled.

Environmental/socioeconomic program

With only limited funding available for environmental and socioeconomic studies, the coordinator of the program, Robert Kamins, decided to focus on the following three aspects of geothermal development: 1) legal and regulatory aspects, 2) economic implications, and 3) environmental impacts. These topics had a direct bearing on the social, economic, and political factors that would help or hinder the implementation of geothermal energy in Hawaii.

The first aspect, the legal-regulatory research, involved the complex questions of ownership and government regulation. Because Hawaii public law did not cover geothermal resources, it was uncertain whether geothermal steam was publicly or privately owned. In order to clarify this issue, the research team would first have to examine how other areas in the United States settled the ownership question. These approaches would then have to be compared to the relevant statutes in Hawaii, and alternative solutions proposed that were consistent with Hawaii's statutes. Of particular importance in this regard was whether geothermal resources could be classified as mineral, water, or a substance unique in nature. If geothermal resources were classified as mineral, some would be owned by the state under mineral rights clauses; if they were classified as water, they would be owned by private landowners through legal precedence; and if they were classified as unique in nature, their ownership would be uncertain. This situation was further complicated by two issues. First, some of the land deeds issued during the early 1900s did not reserve to the state of Hawaii the exclusive ownership of any subsurface minerals. Since it was not known how many of these deeds existed or where the land pertaining to them was located, ownership could be determined only by reviewing individual land deeds. Second, several groups representing native Hawaiian rights claimed that the geothermal resources belonged to native Hawaiians and that their ownership was upheld by the state of Hawaii constitution.

In examining the regulatory issues, the environmental/socioeconomic team would have to address questions such as: Which government agencies, if any, should possess authority over the drilling, land use, and development of geothermal energy? What safety requirements should be adopted for drilling and for geothermal power plants? What environmental safeguards should be imposed upon geothermal development? How should the public interest be protected?

A fundamental issue regarding these questions was the multiplicity of government agencies potentially involved in regulation. On the federal level these agencies included the Environmental Protection Agency (EPA) and the Energy Research and Development Administra-

tion (ERDA). On the state level the agencies were the Department of Health, the Department of Transportation, the Department of Planning and Economic Development, the Department of Land and Natural Resources, the State Energy Resources Coordinator, the Department of the Attorney General, the Office of Environmental Quality Control, the Hawaii State Legislature, the Public Utilities Commission, and the Department of Regulatory Agencies. On the county level the agencies were: the Department of Public Works, the Department of Research and Development, the Department of Water Supply, and the Planning Department.

The second research topic – the economic impact of geothermal development – involved the research team building an econometric model that would provide projections to the year 1980. To begin this task, the researchers would collect data on the cost, source, amount, and distribution of Hawaii's present energy use. Data would also be collected on the cost and production of geothermal energy around the world. From this data, the researchers would make certain assumptions about energy prices. Then, after building a dynamic model, estimate the demand for geothermal energy under varying supplies. Projections could then be made of the resulting impact upon employment, population dispersion, industrial growth, public revenue, and economic growth.

The third research task – environmental analysis – would monitor the ecologic impact of any geothermal well or power plant developed by HGP. Initial studies would involve researchers collecting baseline data of the vegetation and wildlife in the drilling area. Of particular concern, however, was the Ghyben-Herzberg lens, which supplied much of the island of Hawaii's fresh water. A medium or deep geothermal well might penetrate the lens, thus endangering the water supply. To provide information about the impact of drilling, researchers would initially measure nearby springs for salinity, temperature, and chemical characteristics. Then they would establish a program to monitor the springs for any deviations from the baseline measures. Eventually, the environmental program would complete a comprehensive environmental impact statement.

In late 1973, the program team began working on the legal/regulatory aspects and the economic implications. The environmental analysis, however, could not be initiated until a potential drilling area was designated, and in late 1973, it was uncertain if HGP would receive drilling funds. Nonetheless, there was an urgency for the study on legal implications because the Hawaii State Legislature was considering legislation to clarify the ownership of geothermal resources.

To assist the legislators, the research team completed, in February 1974, a preliminary analysis of all geothermal ownership options and their consequences. Aided by this study, the legislature passed the state's first geothermal law. It classified geothermal resources as mineral, thus reserving them to the state under mineral rights provisions. Work on the regulatory aspects and the economic impact continued through 1974.

Overall Coordination and Management of HGP 1973-1974

While each program's research was being conducted, John Shupe attempted to ensure continued support for HGP and to maintain the project's overall cohesion. He conferred regularly with federal, state, and country agencies, made presentations of the envisioned HGP program at public symposiums and at international conferences, and formed contacts with a widespread network of geothermal experts, who would provide HGP with advice, information, and assistance. In August 1973, Shupe also formed the Hawaii Advisory Committee (HAC) and the National Liaison Board (NLB).

The HAC was composed of Hawaii's business, political, and community leaders such as the president of Hawaii's major electric company, the director of the state Office of Environmental Quality, the director of the state Department of Planning and Economic Development, the director of a leading environmental group, the president of the Congress of Hawaiian People, and officials from the County of Hawaii. Since these individuals represented the groups that formulated Hawaii's energy policy, their support was critical for the successful development of geothermal energy. Moreover, many of the groups, particularly the state and county officials, strongly supported the development of indigenous alternative energy sources. Therefore, it was natural that the project include them in an overall cooperative effort. The first HAC meeting was held in October 1973, and the group decided to meet semiannually.

The NLB was composed of geologists, geophysicists, and engineers from the U.S. mainland. Experts on geothermal power development, they would monitor and advise HGP on its progress and direction. Since they also worked for key agencies such as the National Science Foundation (NSF) and the United States Geological Survey, they would be extremely influential in ensuring continued federal funding for the project. The first NLB meeting was scheduled for early 1974.

Maintaining the overall cohesion of HGP was the project director's most difficult but most important task. He realized that the project was, to a certain extent, naturally segmented because each program conducted very different kinds of research. Moreover, some separation was necessary to give each program the flexibility and independence necessary to accomplish its individual goals. At the same time, however, he also realized that the ultimate goal of each research program was to support the generation of geothermal power in Hawaii. This goal provided the driving force for HGP and integrated the research programs with one another. Thus, the project director had to encourage all program coordinators to keep the ultimate goal in mind and to avoid concentrating on research that was not relevant to the project's overall goals.

Critical Events and Decisions of 1974

At the beginning of 1974, HGP was increasingly embroiled in the major policy question of whether or not to establish and proceed with an experimental drilling program. The project director felt that the project had to make progress by moving in the direction of drilling an experimental well. He thus advocated the establishment of a drilling program. The geophysics program coordinator felt that further research had to be conducted before HGP could even consider a drilling program. However, the engineering and socioeconomic program coordinators supported the establishment of a drilling program. Other HGP team members, particularly Agatin Abbott, a professor and the chairman of the Department of Geology and Geophysics at the University of Hawaii, supported a drilling program because it was the only way to actually determine if a usable geothermal source existed. However, a final decision could not be made immediately.

Against the background of this unresolved policy issue, Shupe convened the first meeting of the National Liaison Board. The meeting was held in February 1974 on the island of Hawaii, where any potential drilling would occur. The meeting was intensive. The director of the NSF's Advanced Energy Research Program outlined the foundation's interest in HGP, emphasized the crucial role of the NLB in evaluating HGP's progress, and pointed out that NSF could not fund commercial exploratory drilling but could fund a research drilling program.

Then, each HGP program coordinator presented a progress report. The engineering coordinator described the reservoir engineering and mathematical work to date; the environmental/socioeconomic coordinator described the Hawaii State Legislature's efforts to establish a legal framework for the ownership of geothermal resources. Most of the meeting was spent, however, on the progress of the geophysical program. Initially, the geophysics coordinator described the infrared air photo survey and the electrical resistivity surveys and also presented data from his deep (4,000 feet or 1,257 meters) drill. A review of surveys conducted prior to the formation of HGP was also presented and a lively discussion ensued. Board members, HGP personnel, and persons in the audience asked probing questions and offered interpretations of the geophysical data.

At the end of the meeting, the NLB could reach no consensus on which sites had greatest geothermal potential. But it did agree on recommended courses of action for HGP. The NLB felt that HGP should move rapidly on establishing a research drilling program. There was no other way to test the theories and interpretations. The NLB further recommended that the coordinator of the drilling program be Agatin Abbott. Abbott was the senior geologist on the research team and he had conducted the aerial infrared surveys. He also was an advocate of an early drilling program and had vigorously supported its establishment. NLB also advised that a site selection committee be formed. This committee should be composed of senior geologists and geophysicists, who would collectively make decisions about all aspects of the drilling

program, including the number of research wells and the location of all drill sites. Abbott was recommended to chair the site selection committee. After reaching a consensus on these recommendations, the board members concluded the first NLB meeting.

Shupe informed the Hawaii Advisory Committee about the National Liaison Board's recommendations and the HAC likewise encouraged the organization of a drilling program. The HAC also told Shupe that they would aid HGP in securing state government funds to support the drilling. With the pledge of HAC's support, it was decided to request funds from the Hawaii State Legislature, which was just beginning its 1974 session. In this process, a lawyer first drafted an appropriations bill requesting \$500,000 from the state of Hawaii government. The bill was then introduced to the legislature and each program coordinator testified before the legislature's appropriations committees about his program's progress and about its relationship to the development of geothermal energy in Hawaii. The keystone of the testimonies was a discussion of geothermal drilling by Abbott. Since a drilling program had not yet been formulated, he could provide only a general overview. Nonetheless, the overview was sufficiently detailed to capture the legislators' interest. At the conclusion of the formal testimony, Shupe was assured that HGP would receive support. But he would have to wait until the legislature formally approved the funds and until the governor released them.

In late February 1974, the project director determined that it was timely for the HGP to formally establish a drilling program. Thus, the HGP executive committee was convened to discuss the issue and reach a decision. At the meeting, Augustine Furumoto, the geophysics coordinator, stated that establishing a drilling program was premature; HGP funds could be most usefully spent for further geophysical surveys and data interpretation. In response, Shupe argued that both the NLB and the HAC, the two advisory groups, had strongly recommended the formulation of a drilling program. Moreover, it was an appropriate time to establish and proceed with such a program because the project had to progress toward its long range goal of generating geothermal power.

Paul Yuen, coordinator of the engineering program, Robert Kamins, coordinator of the environmental/socioeconomic program, and other members of the executive committee also pointed out that the geophysical surveys had generated a large quantity of data. The data had been interpreted and varying predictions of the subsurface conditions had been made. But the only way to check the interpretations and to verify the accuracy of the predictions was to actually drill. Finally, the drilling proponents argued, the area in which the drilling would occur was one of the most thoroughly studied geological regions in the world. The HGP, the University of Hawaii, the United States Geological Survey, the state and county governments, and other universities had conducted geological and other survey expeditions in the area. Surveys such as geodetic, gravity, deformation, seismic refraction, magnetic, and thermal had already been conducted. An experimental drilling program was thus long overdue.

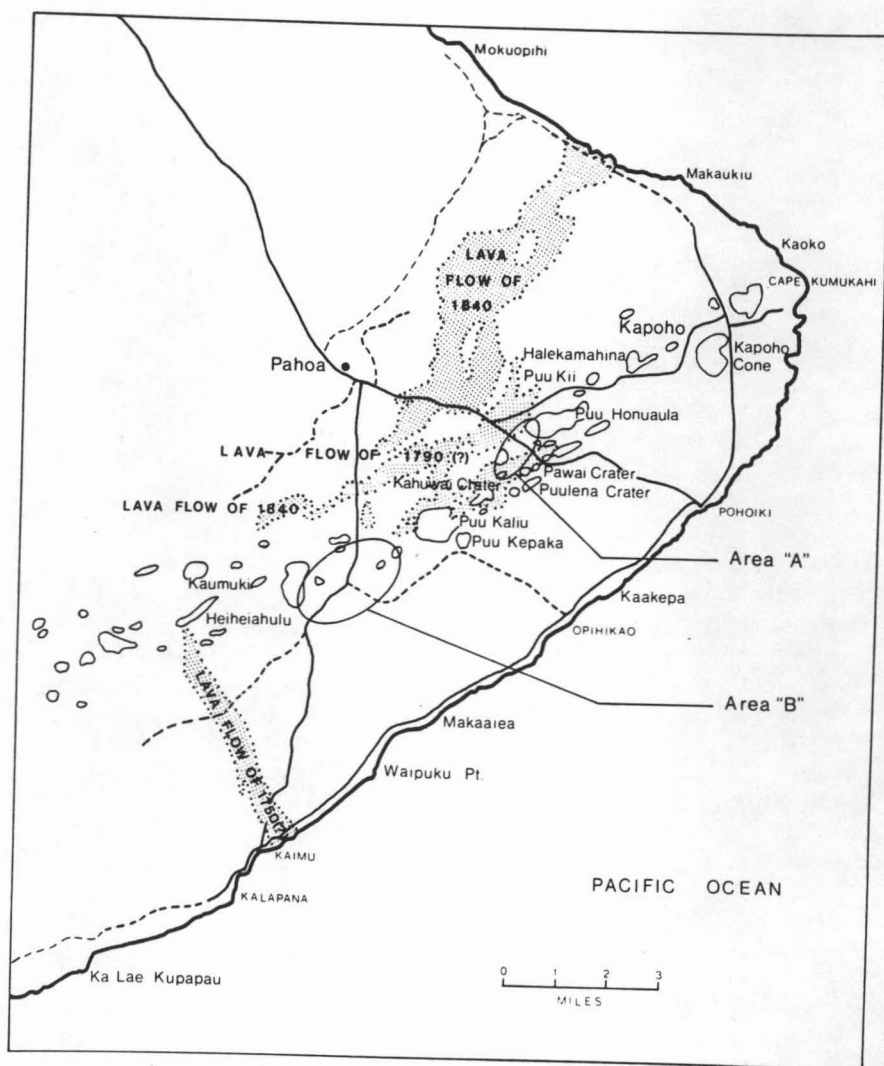


Fig. 3.8. Locations of Area A and Area B.

After discussing the issue for a while longer, the executive committee voted to establish a drilling program. Abbott was appointed the program coordinator, and Shupe provided him with a small budget to initiate planning activities. Abbott's first act as coordinator was to form a site selection committee, which would assist in planning and in making decisions for the program. By March 1974, then, HGP consisted of four research programs with several advisory and policy boards. (HGP's organizational structure as of April 1974 is illustrated in fig. 3.7.)

Following these actions, the project director turned his attention to fiscal management. He realized that HGP would require more time and more money to complete the research programs presently under way. Additionally, a large grant was required to support the research drilling program. It was therefore decided that each program coordinator would assist in the preparation of: 1) an eight-month budget extension to fund their current activities, and 2) a new proposal to fund an experimental drilling program, including related activities.

Design: Completing the Proposals and the Drilling Program

From March through June 1974, each research team continued to make progress on its scheduled research tasks. The engineering program's researchers continued working on the numerical modeling and the well testing program. Additionally, they continued designing the optimal geothermal plant. In the environmental/socioeconomic program, research continued on the legal-regulatory issues and the economic analysis.

Finally, in the pivotal geophysics program, work was being done on a wide variety of exploratory surveys. The geophysics researchers completed building a wire loop magnetic induction system, and implanted 12 pairs of electrodes deep into the earth by air-dropping them in inert missiles. This system was designed to follow up on the initial electrical surveys and would help to determine whether or not geothermal resources existed at depths of 1.24 miles (2 kilometers). Other surveys that continued under the auspices of the geophysics program included a microseismic survey, a magnetic survey, and geochemical surveys of ground water. Also, during this time period Donald Zablocki of the United States Geological Survey, with the assistance of HGP team members, began an electrical self-potential survey of the Puna area. Self-potential surveys had, in the past, proved extremely useful in helping locate potential geothermal sites.

Important as the geophysical research was, however, the top priority of HGP increasingly shifted to completing the budget extension and the experimental drilling proposal. Preparing the budget extension was relatively simple but time consuming. Each program coordinator wrote a progress report elaborating on his program's research results, on the problems encountered, and on the funding necessary to complete the research. The project director reported on the overall status of the

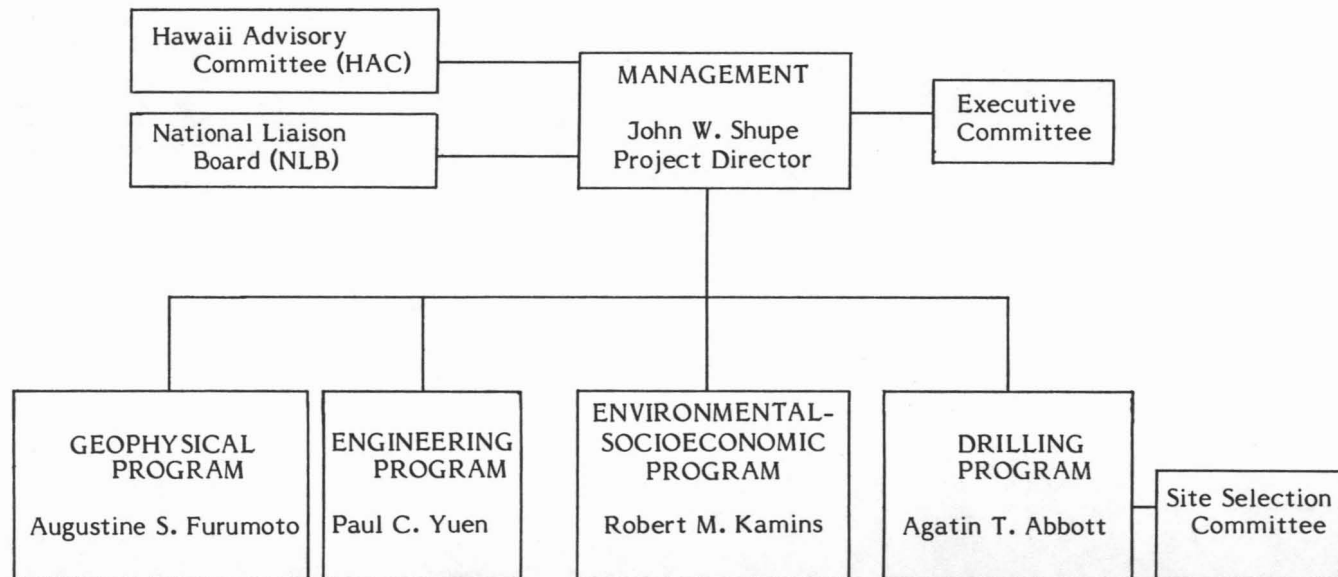


Fig. 3.7. Hawaii Geothermal Project – organizational chart, 1974.

project and justified the requests for a time extension and for additional funds. When completed, the 108-page budget extension requested an additional \$340,000 extended over an eight-month period ending in December 1974. It was submitted to NSF in April 1974.

The executive committee then met to discuss the preparation of the experimental drilling proposal. The geophysics coordinator emphasized that the tone of the proposal should stress the project's continuing experimental focus. The intent of the drilling program would thus be to check the geophysical predictions and interpretations – not to discover a usable geothermal resource. In response, the project director and the other program coordinators acknowledged the experimental nature of the drilling, but added that the ultimate goal of the project was to develop the capability for generating geothermal power. This meant that it was crucial to discover a usable geothermal source. They thus emphasized that the proposal should retain a judicious balance between pure research and the development of practical applied techniques.

After discussing this issue, they decided that a sharp restatement of the overall goals of HGP was necessary to keep the drilling proposal in perspective. These goals included:

1. Improvement of geophysical survey techniques for locating underground heat resources.
2. Identification of potential geothermal resources, initially on the Big Island. . . .
3. Experimentation with deep-drilling techniques for subsurface heat.
4. Development of efficient, environmentally clean systems for conversion of underground heat resources to useful energy.
5. Completion of socio-economic and legal studies for conversion of underground heat resources to useful energy.
6. Establishment of environmental baselines with which to monitor subsequent geothermal development.
7. Development of a geothermal production field and prototype power plant on the Big Island. . . .(7)

With these goals in mind, all agreed that the proposal would request funds for each program to continue its research tasks. However, the priority research tasks would be those that directly supported or related to the drilling program. Finally, they agreed that the proposal would give highest priority to the drilling program itself.

The task of writing up the proposal was divided among the program coordinators; each coordinator would be responsible for the write-up of his program's plans. The project director would coordinate work on the

proposal, assemble it, make it cohesive, and compile all of its financial and administrative sections. The program coordinators completed the plans for their programs in May, and, by late June 1974, it was completed. It was divided into four sections; a brief description of each section follows:

Geophysics program. During the time period of the proposal, work would continue on all geophysical surveys that were not yet completed; these would probably be the microseismic studies, the magnetic studies, and the geochemical surveys. Additionally, follow-up studies would begin; these would include a geochemical survey, thermal surveys of well water, and mathematical modeling. Also, in early 1975, the geophysics team would make a preliminary analysis and interpretation of the data to help the drilling program determine the most useful sites for drilling. Finally, two new tasks would be undertaken: 1) a hydrology study of the Puna area, and 2) a study of the physical property of rocks in the same area. The hydrology study would analyze geochemical data to determine the source of geothermal water, the way it circulated beneath the earth, and the process in which it recharged the geothermal reservoir. The physical property of rocks would measure the thermal conductivity of the drilling area.

Engineering program. During the grant period, research would continue on the optimal geothermal plant design and the numerical modeling. However, the priority task would be carrying out the well testing program, which the engineering team had designed. The testing program was composed of three sections: 1) bore hole tests, 2) well completion methods, and 3) well tests.

1. Bore hole tests would be conducted during the drilling. Researchers would continuously monitor the temperature and composition of geothermal fluid; and at regular intervals, as well as periods of sharp temperature increases, they would take formation logs. Formation logs would include information such as temperature, pressure, and composition of the fluid in the drill hole, as well as the type, density, and porosity of the rock surrounding the drill hole. The engineering researchers would obtain this information by drawing core samples of the earth and by lowering a probe into the drill hole. The bore hole tests would not only provide valuable data, but also would help determine how deep to drill and when to stop.
2. Well completion involved deciding how to complete the drill hole and what kind of equipment to use to build the well head. If the well tapped a favorable geothermal reservoir, the drill hole would be prepared for further testing by installing a slotted liner, or a gravel pack. After the hole was completed, the well head would be assembled. The specific equipment to complete the well head would be chosen after further study. But the well head design required: a) a valve assembly to control the flow of steam from the well, b) a silencer to reduce the roar of the steam as it flashed from the well,

- and c) a centrifugal cyclone separator to separate the well's steam and hot water. The final task of well completion would be starting the well. If the well did not flow naturally, the engineering team planned to force the geothermal fluid to the surface by injecting compressed air into the hole; thereafter the natural pressure and heat of the geothermal reservoir would force the steam and water up the drill hole to the well head.
3. Well testing would occur in two stages, a downhole fluid measurement stage and a well-flow stage. In the downhole stage, the engineering team would lower measuring probes into the well and record the temperature, pressure, and flow rate of the geothermal fluid. This information would help the engineers to estimate the life span and generating capacity of the geothermal reservoir. After allowing the subsurface conditions to stabilize for at least one month, the engineers would initiate the flow testing. The steam would then be allowed to flow out of the well for extended periods, during which the engineers would measure the pressure, temperature, and mass flow rate. This data would enable them to estimate the well's generating capacity.

Environmental/socioeconomic program. During the grant period, the researchers on this program would complete the legal-regulatory studies and the economic studies. They would also begin two new tasks, environmental monitoring and land use studies. The environmental monitoring would include a baseline data collection of the chemical, biological, and physical characteristics of the area. This baseline would establish the standard against which to measure the impact of drilling. If the investigations indicated that the environment would be adversely affected, drilling plans would be altered. Finally, the fumes produced by the discharge of geothermal steam would contain gases such as ammonia and hydrogen sulfide. To measure the quantities of gas being released into the atmosphere, a special team of scientists would conduct air quality studies. The land use studies would provide two crucial bits of information. First, they would provide information on the zoning codes and the land use laws that might restrict the well location and drilling operation. Second, the studies would identify the owners of potential drill sites. Once this information was compiled the team members would negotiate with the owners for the rights to enter their land and to drill for geothermal resources.

The drilling program. This was the focal point of the proposal. Not only would drilling demonstrate the success of HGP's initial research efforts, but also it would provide dramatic evidence of HGP's progress toward generating geothermal power. Based on the work of each research program, as well as previous geological and ground water surveys, the proposal envisioned drilling experimental holes in three general locations. The most favorable location and the one where drilling would first take place was along the east rift of Kilauea near Puna. In this area, three types of holes would be drilled. These were:

1. Shallow holes (average depth 500 feet or 152 meters) for water samples and temperature measurements;
2. Intermediate-depth holes (2,000 feet or 610 meters) for temperature measurements, rock alternation, water chemistry; and
3. Deep hole (6,000 feet or 1,829 meters or more) to try to reach a potential geothermal source.

To manage all drilling operations, the site selection committee would contract an experienced geothermal engineering firm. This firm would be responsible for overall drilling management, including: drawing up a drilling contract, subcontracting the drilling, managing the drilling operations, drawing up safety regulations, cleaning up the site, controlling the finances, and handling all other operational aspects. The site selection committee would decide upon the location, number, diameter, and depth of all drill holes. Additionally, the committee – in conjunction with the engineering, geophysics, and environmental/socioeconomic programs – would determine the types of scientific measurements, when to take them, and how to assess the results. The site selection committee would also hire the geothermal engineering firm.

In the description of the drilling plans, no specific drill sites were identified. Instead, the plans provided detailed maps of the general areas being considered for drilling and provided the geophysical data which indicated that geothermal resources existed in these areas. The site selection committee would choose specific sites after the results of other geophysical surveys were received from the field and after the socioeconomic program indicated which areas.

The proposal was submitted to the National Science Foundation in July 1974 by the project director, John Shupe. The proposal established a one-year activity period, January-December 1975, and requested \$2,000,000, of which \$1,200,000 would be allocated to the drilling program.

PHASE 2: SELECTION, APPROVAL, AND ACTIVATION

Selection and Approval

Initial success and some revisions

In May 1974, formal notice was received that the Hawaii State Legislature had approved the Hawaii Geothermal Project's request for drilling funds; HGP would be allocated \$500,000, provided that the project also received federal matching funds. Later in the month, the National Science Foundation (NSF) approved the budget extension. NSF would grant the project \$217,000 to enable the research teams to continue working on their tasks through December 1974. The NSF program manager further informed HGP that it would receive an additional \$118,000 in 1975 to complete the research.

In July 1974, as previously discussed, Shupe submitted the multi-million-dollar experimental drilling proposal to NSF. Since the amount requested was so large, it would take six months to review. While the proposal was being reviewed, each research team continued with its research tasks. Then in September 1974, Shupe conferred with the NSF program managers about the proposal. At this conference they informed him that NSF would not fund such an expensive drilling program, but that HGP could expect to receive approximately \$500,000, which was enough to drill a single deep well. Moreover, HGP should specify a drill site.

Shupe informed the HGP executive committee of the funding constraints and then told the program coordinators that they had to revise their programs. The revisions were to include: the geophysical evidence and analysis that had been completed since the submission of the initial proposal, reductions in the level of spending and activity of each program, new drilling plans based upon the new budget constraints, and specific locations of each drill site. Each research team proceeded with the revisions; the bulk of the work, however, was to be done by the geophysics team and the drilling program team in conjunction with the site selection committee.

The site selection committee met in October 1974 to draw up new drilling plans. After discussing all options and reviewing all the available data, they made three decisions. First, they decided that, rather than spend the funds on several shallow holes to gather more information, they would drill one deep hole to possibly tap a geothermal source. Second, because funds were so limited, the committee decided that no engineering firm would be hired to supervise drilling operations. Instead, a drilling consultant would be contracted, and the drilling program team would manage the drilling. Third, the committee decided upon the single drill site.

The drill site decision was critical and there was considerable pressure on the committee. Although the drill was explicitly intended to increase scientific knowledge, it was implicitly intended to tap an as yet hypothetical geothermal source. Thus, since only one hole would be drilled, the committee had to select a site that overlay a geothermal reservoir. Adding to the pressure on the committee was scientific uncertainty. The evidence from the geophysical surveys suggested underground hot water, but was not definitive. Several exploratory holes are normally drilled because, as one expert had commented to the committee, "the odds of finding a usable steam reservoir in drilling are one in five, and geothermal search requires a good deal of luck." (8) Nonetheless, the committee had to select the site.

It considered two general locations, Area A, which was the Pahoa anomaly identified by the electrical resistivity survey and Area B, which was the Opikahi anomaly also identified by that survey. Both areas were situated along the east rift of Kilauea near Puna. Area A was about 1,500 feet (457 meters) north of the Puulena Crater; and Area B was located approximately 3 miles (4.8 kilometers) west (see fig. 3.8). After deliberating, the committee chose Area A and desig-

nated a drill site at the apex of the anomaly. An alternative site was also selected approximately 1,500 feet (457 meters) north of the apex.

In choosing Area A, the committee relied primarily on geologic conditions and the self-potential survey. The geological conditions of the region included a history of volcanic activity, an interesting offset in the formation of the rift that indicated the pathway for magma at depth, and ground water with chemical content that indicated a hot water source. The self-potential survey also pinpointed a definitive bull's-eye on the site (see fig. 3.9); this indicated hot water trapped beneath the surface. Geochemical and geoelectrical surveys also tended to confirm the self-potential survey. The committee members thus assessed the potential of finding a geothermal source at either site within Area A as very promising. Area B was also considered to be a site with high potential, but did not have geologic characteristics quite so promising. In sum, the site selection committee was positive and optimistic about the chances of uncovering a geothermal reservoir.

In November 1974, the geophysics program team members met to revise their section of the proposal. They first reviewed all geophysical evidence that had been collected to date and then evaluated the selected drill site. In reviewing the data, they examined the geoelectrical surveys, the magnetic surveys, the seismic surveys, the geochemical analyses, and the self-potential survey. After considerable debate, they concluded that the geophysical evidence required more study and therefore they could not support the site selection committee's optimism. Moreover, their interpretation of the data suggested that a drilling program to search for geothermal resources was unwarranted. The surveys, although indicating a high geothermal potential, could also be indicative of phenomena other than hot water or steam at depth. Thus, until the geophysics program completed a careful and comprehensive analysis of all data, they considered a drilling program to be premature.

The program team members also decided that if a drilling program were to be funded, despite their recommendations, they still could not support the location chosen by the site selection committee. In elaborating on this position, the geophysics program coordinator wrote in a summary report:

The Site Selection Committee for the drilling program, which is quite independent in organization from the geophysics program, met in November to select a drilling site for the renewal proposal. As far as the geophysics program is concerned, no special site can be recommended for geothermal exploration, but a hole could be recommended to check geophysical data. The committee chose a site based on self-potential data and geological formation. The geophysical program agreed to go along as a hole at that site will also have value in checking out gravity and magnetic data.(9)

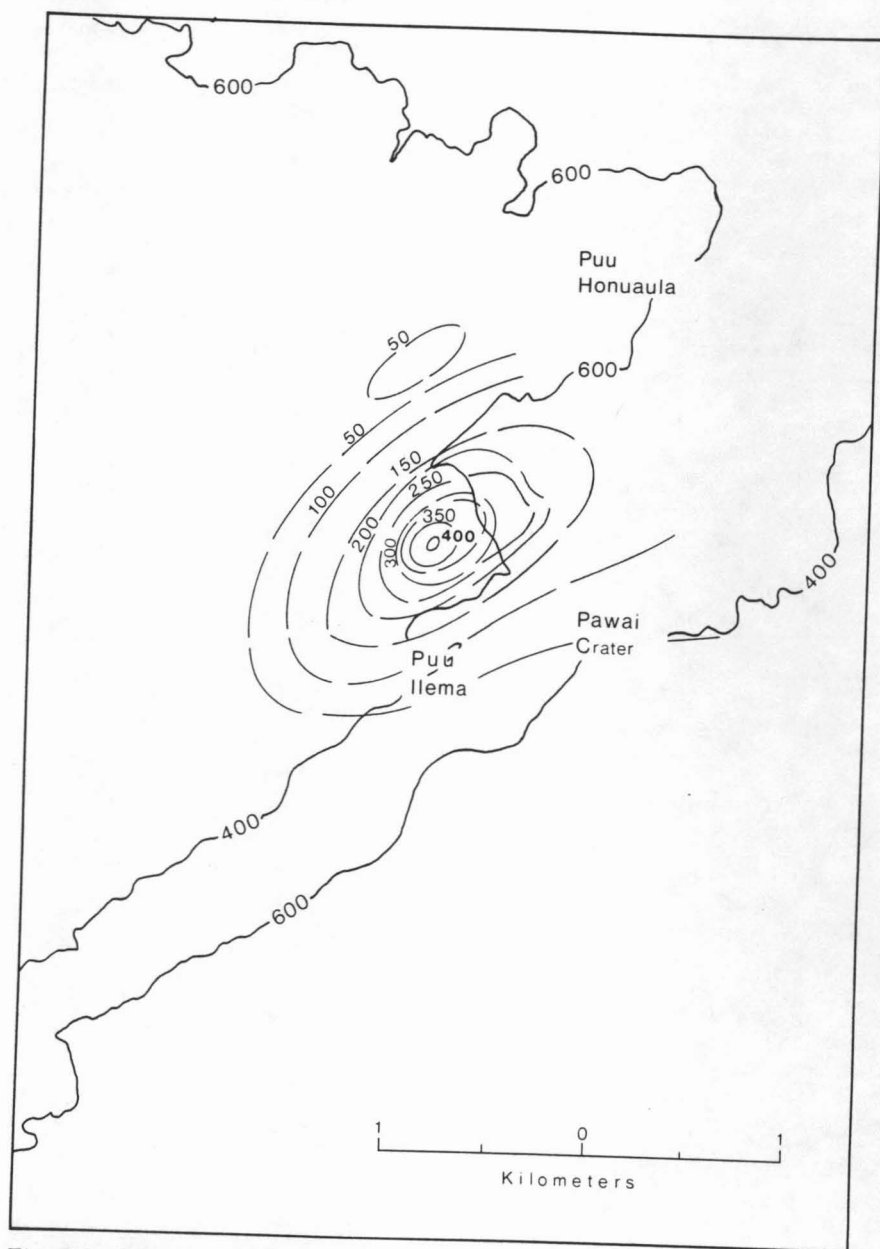


Fig. 3.9. Self-potential mapping of Area A.

Source: Hawaii Geothermal Project, Quarterly Progress, no. 4, March 1, 1974, June 30, 1974, pp. 5-25.

Despite the optimism of the site selection committee and the skepticism of the geophysics program, the revised proposal was written. As could be expected, it reflected the divergent outlooks. On the one hand, the geophysics team emphasized in the proposal that the geophysical data was ambiguous and that further surveys should be undertaken. Moreover, they endorsed a drilling program, not because it had potential for uncovering a geothermal reservoir, but because it could test geophysical interpretations.(10) On the other hand, the site selection committee was very positive about the site and about the potential of finding a reservoir. They stated in the proposal that "probing to depths where we now have no factual information would be most beneficial and we could conceivably arrive in the upper portion of a potential geothermal resource."(11)

The geophysics program coordinator was dismayed by the overall proposal. He later commented that "the fine distinction, exploratory hole to test data vs. exploratory hole for geothermal source, was lost in the writing of the proposal."(12) Nonetheless the revised proposal was submitted to NSF in December 1974.

Apprehension and then approval

While the Hawaii Geothermal Project waited for a decision on funding, the site selection committee received outside opinions concerning the site. Of particular interest was a letter written by George Keller to John Shupe. In the letter Keller expressed the opinion that the committee's reliance primarily on the self-potential survey made him skeptical. In response to this opinion, the committee held a meeting in January 1975 to reassess the site. At the meeting, the committee reexamined their decision in light of all the information which they had received; and they decided that the originally selected site was still the area with greatest potential. The geological structure was favorable, and the geoelectrical and geochemical surveys still indicated subsurface hydrothermal activity.

Later in the month and during February 1975, John Shupe conferred with NSF officials about the revised proposal. He also met with officials from the Energy Research and Development Administration (ERDA). ERDA was the federal government agency responsible for the development of the nation's new energy sources; it would assume from NSF the funding responsibility for an approved drilling program. During the meetings with the officials from both agencies, Shupe received assurance that the proposal was high priority and that it certainly would be approved. NSF even sent a staff worker to Hawaii to advise Shupe and the drilling program team members on preparing invitations to bid for the proposed drilling. Despite the assurances, however, the two agencies had not yet completed the proposal evaluations.

In early March, Shupe received the evaluation; it concluded that there was insufficient geophysical data and analysis to justify a drilling program, especially since the implied intent of the drilling was to tap a geothermal source. The geophysics coordinator commented that he had

predicted such an evaluation because there had been insufficient time to conduct a thorough interpretation of the data. The geophysics team thus concentrated on completing a thorough analysis.

By the end of the month, a preliminary interpretation of the geophysical surveys was completed. Using the data from the gravity, magnetic, and microseismic surveys, the geophysics team projected the shape, width, and depth of the dike complex in the proposed drilling areas. The dike complex, or intrusive zone, was projected to begin about 2,953 feet (900 meters) below sea level. It was approximately 1.98 miles (3.2 kilometers) wide, with a vertical extension of about 2.49 miles (4 kilometers) and had the shape of a long horizontal rectangular prism with vertical walls. A complete interpretation of all the data was not made, but early interpretations tended to confirm that there was a possible geothermal resource at Area A.

More important, there was now adequate data and interpretation to justify an exploratory drilling program. The available data and the interpretations were sent to ERDA.

Then, in late April 1975, ERDA informed Shupe that the proposal had been approved. The Hawaii Geothermal Project (HGP) would receive \$1,064,000 for the period May 1975-April 1976. This amount, when added to the \$500,000 allocated to the project by the state of Hawaii and to the \$45,000 given to the project by the Hawaiian Electric Company, amounted to a total of \$1,609,000.

Activation

Preliminary activity and key decisions

The project director had actually begun preparing for the drilling activities long before he knew whether HGP would receive drilling funds. As early as October 1974, action was taken to acquire legal permission for the potential drilling. Robert Kamins, the coordinator of the environmental/socioeconomic program, had a University of Hawaii attorney prepare a model right-of-entry permit. The permit was a document granting the landowner's permission for HGP to use his land for drilling. In November, after the site selection committee had chosen the primary and an alternative drill site, Kamins identified the primary site owners as the Tokyu Land Corporation. He sent the corporation's managers a copy of the permit; but after reviewing it, the managers refused to grant HGP drilling permission. Kamins then began negotiations with the owners of the alternative site, the Kapoho Land Corporation. Since this corporation was not developing the site, it agreed to sign the right-of-entry permit. Specifically, the permit granted HGP the rights to enter, to prepare, and to drill the land for a fee of \$1. Since HGP was a research project the question of ownership was not relevant. However, if a geothermal resource was discovered, ownership would have to be determined before it could be commercially exploited.

Fully expecting drilling funds to be approved, the project director and the program coordinators continued preparing for the drilling phase. In late January 1975, Abbott, along with the drilling program team and a consultant from the National Science Foundation, prepared invitations to bid on the proposed drilling. The invitations were sent to a number of firms in Hawaii and on the mainland United States. By March, however, drilling funds still were not approved by the Energy Research and Development Administration, so Shupe had to recall the invitations and to wait for the funding decision.

An HGP executive committee meeting was held in late April. At the meeting it was announced, as has been previously discussed, that ERDA was satisfied with the information provided by the geophysics team in March and that firm assurances had been given to Shupe that the drilling would be funded. Official approval of the funds would be forthcoming before the end of the month. The geophysics program coordinator then commented on the selected drill site, Area A. He said that he had completed a more thorough interpretation of the geophysical data, and now he had serious doubts about the geothermal potential of Area A. He felt that Area B, a location which the committee had also considered, had greater geothermal potential. Because of these doubts, another site selection committee meeting was scheduled for May 1975. It was also decided to invite George Keller to the meeting, since he had also expressed doubts about the site.

By May 1975, ERDA had formally approved funds for the drilling; thus the site selection committee meeting took on added significance because it would be the final opportunity to reconsider the drill site. To begin the meeting, the geophysics coordinator commented that Area B was more favorable than Area A because the area of anomalous low resistivity in Area B was considerably larger than in Area A. More disturbing still was that Area A registered high magnetic readings. Since the Hawaiian basalt loses its magnetism above the Curie point, the high magnetism indicated that Area A might not supply enough heat for a geothermal reservoir. Adding support for Area B, George Keller noted that seismic data indicated that rocks in this area had a Poisson's ratio of 0.4. This indicated fractured rock which could possibly allow enough hydrothermal flow to create a reservoir.

In response to these comments, other committee members pointed out that when electrical data from several sources was analyzed, indications were that the anomalous resistivity lows were more definitive in Area A than in Area B. Moreover, the self-potential survey indicated an unambiguous bull's-eye at Area A; and self-potential surveys were found by the U.S. Geological Survey to be the single most useful method for identifying anomalous thermal areas in Kilauea. Finally, there was a moderately high sound intensity of 9 decibels (db) in the vicinity of Area A, which indicated geothermal activity at depth. The high level of magnetism could not be explained, but the magnetic implications conflicted with geochemical and temperature data. A previous geothermal test well located downslope from Area A was 193°F (90°C), and the water in the well contained several times the

normal level of silica and chloride, all of which strongly suggested high temperatures at depth. Finally, the Curie point for theolitic basalt could be as high as 572°F (300°C), which was adequate for a geothermal reservoir.

A comparison of the data was then made between the two areas (see table 3.1). It was concluded that the geophysical data, for the most part, was comparable, although magnetic data favored Area B and seismic data favored Area A.

Table 3.1. Comparison of Data Between Area A and Area B

<u>Source of Data</u>	<u>Area A</u>	<u>Area B</u>
Loop-loop inductive soundings	3-5 ohm/m	5-8 ohm/m
Self-potential survey	450 mV	800 mV
Dipole resistivity mapping	8 ohm/m	5 ohm/m
Downslope well temperature	193°F (90°C)	73°F (23°C)
Downslope well chloride content	3,410 mg/liter	—
Downslope well silica content	174 ppm	1 ppm
Ground noise	4-9 db	background only
Magnetism	high	low

The deciding factors would thus have to be geologic, and geology strongly favored Area A. First, Area A lay over the dike complex, while Area B was somewhat astride of it. The dike complex was formed by the consolidation of magma in numerous fissures; thus it formed a potential reservoir of heat. Second, Area A was located directly above an offset in the 1955 volcanic eruptions. These eruptions proceeded to the northeast, stopped, and then resumed in a significantly offset southwest direction. It was believed that a concentration of magma could be located in the vicinity of this offset. Third, Area A was coincident with the epicentral distribution of three separate episodes of shallow earthquake swarms in 1970. These episodes might have been caused by magmatic pressure. Fourth, Area A was located in the vicinities of both seismic activities that preceded the 1960 eruptions and the outbreak of the 1955 eruptions. It was thus believed that Area A was in a zone that had a recent heat source. Finally, there were a number of shallow wells downslope from Area A that were significantly hotter than normal. This supported the hypothesis that ground water flowed downslope through a hot source near Area A.

After all the evidence was again reviewed, unanimity could not be reached and so a vote was taken. All members of the site selection

committee, except for the geophysics coordinator, favored Area A. The geological evidence had been the determining factor.

Later in May, Abbott inserted a stake into the ground at the selected drill site within Area A. The overall HGP budget for the drilling phase of the project was then finalized. The allocations were as shown in table 3.2.

Table 3.2. Budget Allocations for HGP Drilling Phase,
1975-1976

Project Director	\$ 30,877
Geophysics	237,977
Engineering	155,972
Environmental/Socioeconomic	59,412
Drilling, including:	
Subcontract	979,000
Consulting	40,000
Site Preparation	35,000
Contingency, Testing	<u>50,000</u>
Total	\$1,609,151

The consulting firm and the drilling and testing programs

Following the site selection committee meeting, John Shupe met with Abbott and the other drilling program team members and they decided to hire a drilling consultant since they had only limited experience in deep-hole geothermal drilling. The New Zealand firm of Kingston, Reynolds, Thoms, and Alardice (KRTA) had earlier been suggested by an NSF official, and thus Shupe began inquiring about the firm. At the May 1975 United Nations geothermal conference, Shupe learned that KRTA had extensive experience with geothermal drilling in New Zealand, the Philippines, and Central America. The firm was also one of the most respected geothermal consulting firms in the world. It was thus decided to contract KRTA's services and an agreement was worked out with R. Kingston, the firm's managing director.

In June 1975, the coordinator of the drilling program, Agatin Abbott, temporarily withdrew from the project because of ill health, and his colleague, Dr. Gordon Macdonald, a University of Hawaii professor of geology and geophysics, assumed the coordinator's role. Later in June, the invitations to bid for the drilling subcontract were sent to 28 firms. Most of the firms, however, were located on the

United States mainland and it would be too costly to ship a rig to Hawaii. Thus, by July 1, the closing date for bids, only one bid had been submitted. This bid was from Water Resources International (WRI), the Hawaii-based company that had previously drilled Hawaii's only deep geothermal well. It was thus decided to negotiate a contract with WRI.

In July 1975, R. Kingston arrived in Hawaii for consultations with the HGP project team. He discussed the overall program with Shupe and held separate conferences with each of the program coordinators concerning the drilling and testing activities. He also spent a great deal of time discussing the drilling with WRI. He then returned to New Zealand and began preparing the drilling and testing plans.

During July and August, Kingston completed both the testing and drilling plans which were based on the special conditions encountered in Hawaii, the needs of HGP, and the experience of geothermal projects in the rest of the world. The plans were crucial for HGP's success. Not only would they be used as the basis for drawing up contractual obligations between HGP and WRI, but also they would be used to guide day-to-day operations. Consequently, the plans were comprehensive and detailed. The drilling plan was divided into three phases: 1) predrilling site activities, 2) the drilling program, and 3) the site restoration. A brief description of each phase follows.

The predrilling site activities were intended to ensure that the site was adequately prepared and that the contractor had adequately mobilized for a deep hole drill. Specific responsibility for completing each activity was divided between HGP and WRI. Some of the more important responsibilities of HGP included:

- Establishing rights of way and building adequate roads to the site.
- Clearing and grading the drilling area.
- Constructing an 8-foot (2.4-meter) deep drilling cellar of size appropriate to support the drilling rig substructure.
- Implanting in the earth a 30-inch (50.8-centimeter) conductor pipe.

Important responsibilities of WRI included:

- Spreading over the drilling area crushed rock sufficiently fine so as to seal the surface from excessive rainwater percolation.
- Constructing on the site a 180,000-gallon (684,000-liter) water reservoir.
- Providing work offices with supply sheds, fences, fuel, and power.
- Obtaining necessary drilling supplies and equipment, such as liner and casing, cement, valves, hole openers, and various drilling bits.

The drilling phase was planned to be fairly conventional. In order to bore the well, the drilling contractor would use a rotary drilling rig, hole openers, various bits, and additional drill collars. As the drilling proceeded, fluid mud would be injected into the hole to cool and lubricate the bit and to remove the cuttings. It was anticipated that this process could penetrate the most difficult rock formations to a depth of 6,000 feet (1,829 meters).

To encase the well, a series of steel tubes, called casings, would be inserted into the hole. From the surface to a depth of 8 feet (2.4 meters), a 30-inch (762-centimeter) diameter conductor pipe would be placed into and cemented to the sides of the bore. A 20-inch (50.8-centimeter) diameter surface casing would then be inserted into and cemented to the sides of the conductor casing. The surface casing would extend from a depth of 3 feet (0.9 meters) to 400 feet (122 meters), with the length of casing below 8 feet (2.4 meters) cemented to the sides of the hole. Another steel tube would then be inserted into and cemented to the surface casing. Into this steel tube another steel tube would be inserted; and finally, if the drilling struck a geothermal reservoir, a slotted liner extending to a depth of 6,000 feet (1,829 meters) would complete the well. Table 3.3 and figure 3.10 elaborate on the planned well construction.

Table 3.3. HGP Casing Program for Geothermal Well

<u>Casing</u>	<u>Diameter</u>	<u>Depth</u>
Conductor pipe	30 inches (76 centimeters)	0 to 8 feet (0 to 2.4 meters)
Surface casing	20 inches (51 centimeters)	3 to 400 feet (0.9 to 120 meters)
Anchor casing	13 3/8 inches (34 centimeters)	3 to 1,000 feet (0.9 to 304 meters)
Production casing	9 5/8 inches (23 centimeters)	3 to 2,500 feet (0.9 to 762 meters)
Liner	7 5/8 inches (18 centimeters)	2,500 to 6,000 feet (762 to 1,829 meters)

The final phase of the drilling program was site restoration. As planned for, the contractor would have full responsibility for removing all equipment, for disposing of all surplus supplies, and for restoring the site.

The testing program

The testing program, which Kingston completed in August 1975, was based on KRTA's experience in different settings around the world. It was intended to be cost-effective, while producing all the necessary data. As stated in the testing program:

The testing program which is recommended in this report is based on the experience which has been accumulated in the development of the geothermal fields in New Zealand. A similar

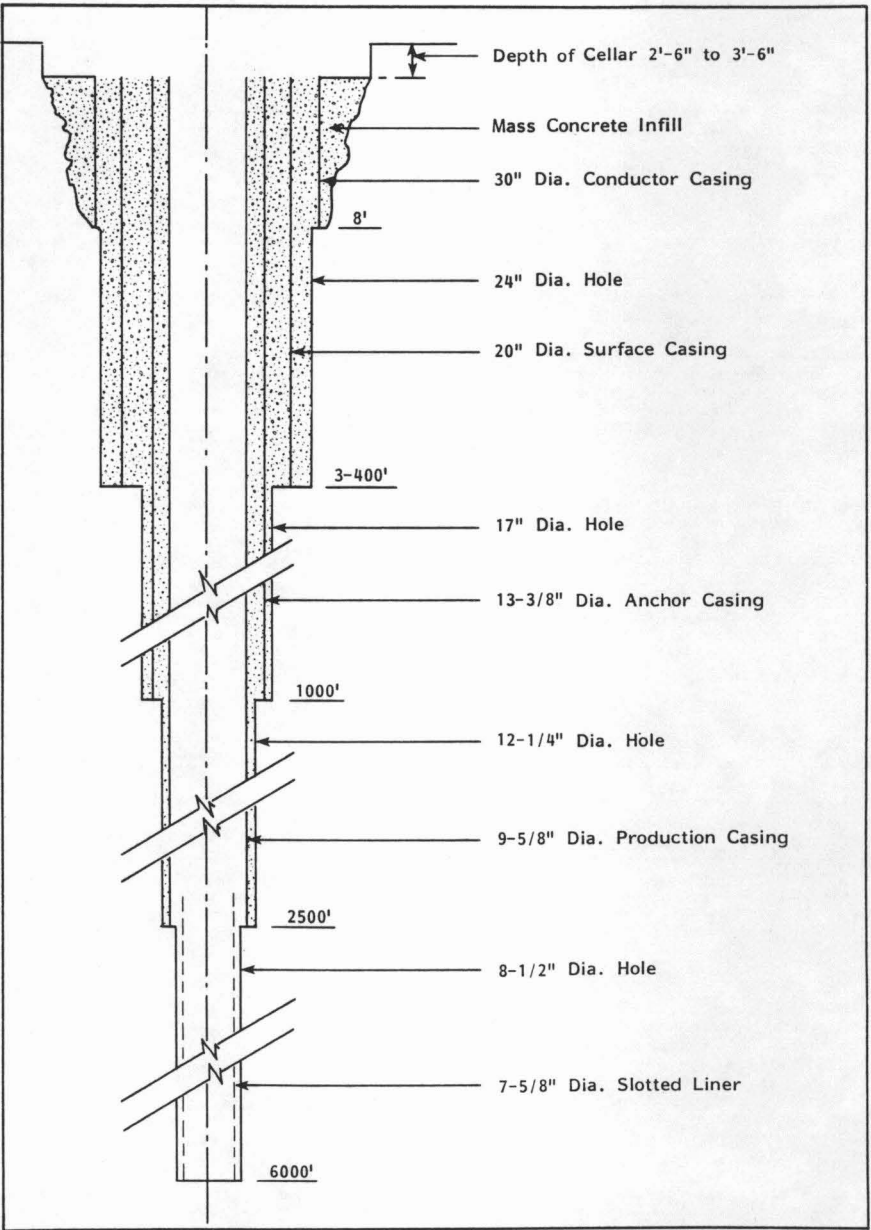


Fig. 3.10. The well casing program.

program is now also being applied in many other countries including the Philippines, Indonesia, Chile, Kenya, Turkey and Nicaragua. The aim of the program is to produce the most useful and factual information which can be obtained from the well, in the most economical manner, and in the minimum time.(13)

The testing program was divided into three stages: 1) drilling tests, 2) drilling completion tests, and 3) output tests.

1. The drilling tests would be conducted during the actual drilling and would help determine how deep to drill and whether there was sufficient geothermal potential to complete the well. Two general types of data would be collected, lithologic data and drilling logs. To derive the area's lithology, geologists would take core samples from the well at approximately 700-feet (213-meters) intervals and cuttings at 5- to 10-feet (1.5-3 meter) intervals. These samples would then be used to complete petrographic and geochemical analyses, which would indicate the structure, composition, and sequence of the formation. The drilling logs, which included neutron, gamma, resistivity, and temperature surveys, would help determine the well's permeability, porosity, and temperatures at various depths. Also a cement bond log would be taken to determine if the cement used for the casing was completely intact. Any flaws or gaps in the cement would have to be corrected with special equipment.

2. Drilling completion tests would be conducted after the well was drilled; they would consist of water loss tests, baseline temperature and pressure measurements, and well starting. The water loss tests were intended to determine the well's permeable zones. To locate these zones, researchers would pump water down the well and take a temperature profile. A gradual change in temperature indicates uniform permeability, while a sudden change indicates a major zone of permeability at or just above the depth of the temperature change.

After locating the possible zones of permeability, the HGP test researchers would try to determine the levels of permeability by pumping water into the well at rates of 100, 200, and 300 gallons (380, 760, and 1,140 liters) per minute. If the rise in water pressure was high it would mean that water in the permeable zones was unable to flow freely out of the well. This would imply low permeability with surrounding rock formation devoid of fissures, fractures, or cracks that would allow a constant flow of geothermal fluid. Lack of permeability meant that the well was nonproductive.

Temperature and pressure of the well would be recorded at regular intervals. When these were stable, they would be the baseline against which all subsequent temperatures and pressures would be compared.

The final aspect of completion testing was to actually start the well. In this process, researchers would remove the top layers of water with compressed air. This would reduce the weight of the column of liquid in the well and enable the pressure from the steam and heat to force the bottom layers of geothermal fluid to flow out of the well naturally and continuously. Once the flow was established, the master valve would be closed and the flow would be shut off.

3. After pressure and temperature had stabilized following the initial well starting, output tests could begin. During output tests, the well would be allowed to flow continuously for periods varying between 7 and 90 days. During each of these periods, the temperature, pressure, mass-flow rate, and heat-flow rate of the geothermal discharge would be measured. These measurements over time would help indicate the well's electrical power potential and life expectancy. The researchers would also collect water and gas samples in order to monitor the chemical discharge of the well.

Mobilizing the project

When Kingston submitted drilling and testing programs to HGP in late August 1975, the drilling subcontract was still being negotiated. The major problem was that Water Resources International was the only bidder, and thus there could be no competitive evaluation. Additionally, the project was jointly funded by the federal government and the state of Hawaii. The acting agencies, ERDA and the University of Hawaii, could not completely agree on what constituted acceptable criteria for evaluating a single source bid. Thus negotiations dragged on.

While the negotiations continued, John Shupe, HGP project director, decided to mobilize the project. He released available funds from the project budget to grade and compact the drill site, to construct the drill rig foundation, and to begin other site preparations. Water Resources International similarly began mobilizing. They purchased a new drill rig and began moving it to the project site. By committing large sums prior to the conclusion of negotiations, Shupe and WRI assumed substantial risk. If negotiations failed, WRI could go bankrupt and HGP could face litigation. Both, however, were confident that points of contention would be resolved satisfactorily. Furthermore, the project was behind schedule, and if they did not begin mobilizing in September, the drilling could not begin until February 1976. It was thus decided to take the calculated risk.

Through September, contract negotiations dragged on. WRI continued to provide the information requested by ERDA and the University of Hawaii; Shupe attempted to mediate and clarify the situation. But federal regulations concerning audit and review processes prevented a swift award of the contract to WRI. Later in the month, R. Kingston, the manager of KRTA, made another trip to Hawaii to help resolve the difficulties. Kingston discussed the subject with the auditors and discovered that they needed more data concerning WRI's cost accounting and the time estimates to complete the drilling. The drilling time was particularly crucial because WRI charged - as was standard practice - by the drilling time expended rather than the depth of penetration. The estimated drilling time was based on WRI's previous experience in drilling Hawaii's only deep geothermal well. For that well, drilling had averaged 100 feet (30 meters) per day. Despite the fact that the HGP well required a hole of considerably greater diameter, WRI assumed it could maintain that rate because it had purchased an improved drill rig that would increase efficiency.

The federal auditors, however, still could not approve the contract because they had difficulty in auditing WRI's records upon which all costs were based. Finally, after correspondence between Shupe and ERDA, the ERDA manager of geothermal development made a special trip to Hawaii to approve the contract. The contract was formally awarded to WRI in November 1975. A summary of the contract's financial accounting appears in table 3.4.

Table 3.4. Subcontract for Drilling Operations

	<u>Contract Estimate</u>
Mobilization	\$120,192
Water reservoir	48,077
Casing (to 3,500 feet or 1,067 meters)	100,000
Consumable materials (to 6,000 feet or 1,829 meters) – bits, mud, cement, etc.	202,431
Well testing equipment and services	50,000
Well drilling, 0 to 3,500 feet (1,067 meters)	199,185
Well drilling, 3,500 to 6,000 feet (1,067 to 1,829 meters)	149,500
Demobilization	9,615
Contingency	<u>100,000</u>
Total	\$979,000

Project organization in December 1975

In December 1975, just prior to beginning the drilling operation, HGP was organized much as it had been February 1974. John Shupe was the overall project director and director of the management program. Each of HGP's other programs continued to be guided by the original coordinators: Augustine Furumoto directed the geophysics program; Paul Yuen directed the engineering program; Robert Kamins directed the environmental/socioeconomic program; and Gordon Macdonald directed the drilling program. Each program coordinator retained fiscal and operational autonomy for his program, and Shupe provided the overall coordination, direction, and leadership. Additionally, each of the program coordinators along with the project director shared responsibility as co-principal investigators of the grant.

Administrative responsibility for each of the programs was held by each of the coordinators. But since the drilling was subcontracted, authority for the drilling program was fragmented. Macdonald, as coordinator of the drilling program, was responsible for all scientific decisions, such as what tests to conduct and when to conduct them. The drilling consulting firm, KRTA, was responsible for recommending specific technical decisions during the drilling and KRTA provided one employee, Warwick Tracey, as the on-the-job drilling supervisor. The drilling contractor, Water Resources International, was responsible for the daily operational activities of drilling, such as supervising the drilling crew, overseeing the equipment changes, and implementing the operational decisions. E. Craddick, president of WRI, would be at the drill site to oversee these duties.

Some of their responsibilities overlapped. For example, any scientific decision, such as when to take a core sample, impinged upon the drilling supervisor's ability to make technical drilling decisions. Sometimes it might be impractical to stop drilling in order to take a core sample. Thus a technical decision would have to be made that might conflict with a scientific decision. Furthermore, KRTA's drilling supervisor could make recommendations to the contractor about the drilling process, but the contractor was directly responsible for the drilling crews and the operations. KRTA recognized these potential overlapping jurisdictions and, to some extent, tried to clarify them. In the testing program KRTA had stated:

The University of Hawaii will appoint to the project a Drilling Manager and a Geologist who will supervise the drilling of the well through the Contractor. They will offer guidance and assistance to the Contractor, but in no way will this relieve the Contractor of the responsibility for the drilling operations. The Contractor is required to provide at all times supervision by a competent toolpusher, and skilled crews experienced in the operations of a drilling rig of this scale.(14)

Even with this clarification, the overlapping authority was bound to create some confusion. Thus, during the actual drilling, the HGP project director referred and resolved any differences among the drilling program team representative, the drilling supervisor, and the contractor. Figure 3.11 illustrates HGP's organizational structure as well as its major funding sources in 1975.

Another administrative difficulty of the drilling was that some of the key people would not be at the drill site. The project director had a dual appointment as the University of Hawaii's dean of the School of Engineering; he would have to remain on the island of Oahu. Similarly, the coordinator of the drilling program would not be at the site after January 1976. He would have to return to his teaching duties at the University of Hawaii campus on Oahu. However, plans were worked out to alleviate this situation. Either the project director or the drilling program coordinator would visit the site once a week and they would

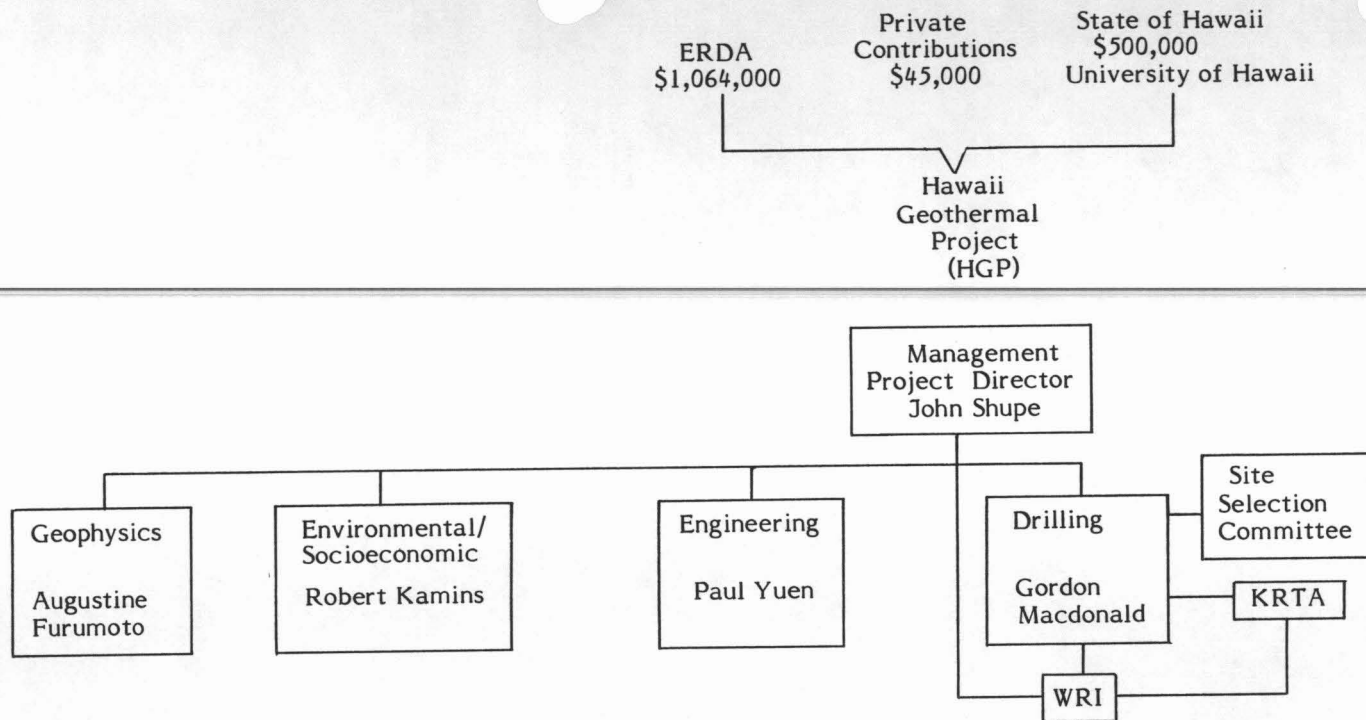


Fig. 3.11. Funding for and organization of HGP, 1975.

communicate with onsite personnel daily. Finally, other project staff would be at the site. D. Palmiter, a graduate assistant with Macdonald, would represent the drilling program and HGP project members from the University of Hawaii campus on the island of Hawaii would help with the drilling. One person in particular, Bill Chen, a professor of engineering at the University of Hawaii Hilo campus, was a key member of HGP's engineering program; he would help with the engineering aspects of the drilling.

PHASE 3: OPERATION, CONTROL, AND HANDOVER

The Drilling Operation

The well site was dedicated on November 22, 1975, and final preparations were made for the drilling operation. WRI assembled the rig, completed installing the plumbing, wired the electrical fixtures, lined the water reservoir, filled it with 180,000 gallons of water, finished constructing the mud pit, and transported to the site equipment such as drill bits, pipes, and casing materials.

Initial drilling

Drilling commenced on December 10, 1975, but progress was slow because the 1955 lava flows had formed a hard basalt layer over the drill site. Drilling the first 400 feet (122 meters) was particularly time consuming. Only limited weight could be placed on the bit as it would not remain vertical. Further delays were caused by the high standards of the casing program, which stipulated that a 20-inch (51-centimeter) diameter surface casing be installed from the surface to a depth of 400 feet (122 meters). This meant that WRI had to initially drill into the lava with a 9-inch (23-centimeter) bit and then use hole openers to progressively enlarge the bore to 15, 20, and 26 inches (38, 51, and 66 centimeters). In early January, the project director realized that this laborious process put the drilling far behind schedule. He therefore conferred with the drilling supervisor from KRTA and then called Kingston, inquiring about the advisability of abandoning the 20-inch (51-centimeter) surface casing and proceeding directly to install and cement in the 13-inch (33-centimeter) anchor casing. Kingston consulted with his staff and with geothermal experts from the New Zealand government's Ministry of Works. The consensus was that if a productive geothermal resource were discovered, the 20-inch (51-centimeter) surface casing would be necessary in order to prevent blowouts. Kingston thus strongly recommended that HGP adhere to the original casing program.

The project director thereupon decided to continue with the original plan. The hole was drilled to a depth of 400 feet (122 meters), and then progressively enlarged with 15-, 20-, and 26-inch (38-, 51-, and 66-centimeter) hole openers. Finally, the surface casing was inserted into

the hole and cemented in. This time-consuming process took until early February; it had taken nearly two months to complete the first 400 feet (122 meters) of the well.

Although it proceeded much more quickly in March, the drilling was still considerably behind schedule, as numerous operational difficulties were encountered. At one point, six bolts on the rig jack were sheared off and the rig had to be closed down; at another time, the chain drive linking two drawwork engines broke and had to be repaired; at still another time, the pump and generator engines had to be overhauled because of continuous usage; and, as a routine matter, the drill bits deteriorated rapidly in the dense lava. Additionally, numerous core samples and cuttings had to be taken. Although the coring was necessary and planned for, it was still time consuming and added to the pressures of the drilling schedule.

From an administrative perspective, the drilling problems were handled within the overall framework of HGP's drilling supervision, which, as previously noted, was fragmented. For purely scientific decisions, such as when to core, Macdonald, the director of HGP's drilling program, made all decisions. After Macdonald returned to his teaching duties in January 1976, the scientific decisions were made by his on-the-job assistant, D. Palmiter, who called Macdonald daily concerning the scientific investigations.

For simple operational problems, E. Craddick, WRI president and the onsite drilling contractor, made the decisions. In complex and difficult drilling situations, Craddick consulted with Warwick Tracey, who was both the on-the-job KRTA consultant and the drilling supervisor. However, since the duties, responsibilities, and overall authority of drilling supervisor and contractor were not absolutely defined, some conflicts arose when there was a difference of opinion. In one situation, for example, WRI's 20-inch (51-centimeter) hole opener had to be inserted into the 20-inch (51-centimeter) surface casing in order to continue enlarging the hole for the anchor casing. The hole opener would not fit, so the drilling supervisor recommended that the contractor undercut the periphery of the cutters and then rebuild them back up again with hard facing electrodes. The contractor, however, decided to simply cut off the periphery and remove the hard facing of the cutters.

Whenever there was a difference of opinion on a critical activity, the drilling supervisor would have to call Shupe and Kingston. For example, in February and March 1976, the drilling supervisor recommended that the contractor clean up the site and make adequate provisions for the disposal of reject mud and cuttings from the drilling. No site cleanup, however, was undertaken. This forced the drilling supervisor to write to Shupe and Kingston and comment: "Disposal of reject mud and cuttings is still a major problem, and as a result, the site is a mess. The contractor does not seem to appreciate the magnitude of the problem, and his disposal gear is primitive, if not inadequate." (15) Shupe and Kingston then conferred with the contractor and he agreed to improve the disposal of reject mud and cuttings. If the

problem was serious enough, an onsite conference would be held. In resolving the casing program, for example, Shupe contacted Kingston and arranged for him to fly in from New Zealand to meet at the drill site. Prior to the conference, Shupe conferred with the other HGP program coordinators.

Two significant problems

During February and March 1976, two significant problems arose, which went beyond the scope of the operational drilling management. First, on March 18, HGP project staff projected that an additional \$257,000 was required to complete drilling the well to the planned goal of 6,400 feet (1,951 meters). The deficit was caused because the process of installing the surface casing had taken more drilling time than originally estimated. Since payment to WRI was based on actual drilling time, additional funds were required.

The project director first contacted ERDA, and after clarifying the situation through a letter and several phone conversations, received an additional \$150,000. ERDA was extremely supportive because the well was so near completion. WRI was also anxious to see the well be successful, and agreed to donate \$60,000 of its time to finish the well to 6,400 feet (1,951 meters). Finally, the project director met with the program coordinators. He had previously informed them of the drilling deficit and had discussed the possibility of reallocating funds. Now, he stressed that the probability of encountering a productive geothermal resource would be increased if the well were drilled to its original target depth. Moreover, ERDA, the funding agency, was extremely interested in completing the drill to 6,400 feet (1,951 meters). The program coordinator thus agreed to shifting \$47,000 from the research programs to the drilling.

The second significant problem centered on the internal differences of opinion within HGP. As discussed earlier, there was a lack of unanimity on many of the HGP policy decisions. There had never been, for example, unanimous agreement on the decision to establish a drilling program or where to locate the drill site. Now during the drilling, there was still some difference of opinion about the potential of the site. The geophysics program coordinator, after examining more data, believed that the drilling should be terminated at about 4,000 feet (1,200 meters). Among his reasons were: 1) if a geothermal reservoir existed, it should be located between the water table and the dike complex, and 2) gravity, magnetic, and deformation data now indicated that the top of the dike complex was situated at depths between 1,640 feet (500 meters) and 4,000 feet (1,220 meters).⁽¹⁶⁾

The drilling program coordinator had a different opinion. He believed that drilling only to 4,000 feet (1,220 meters) was meaningless for the following three reasons: 1) the purpose of drilling was to discover whether rocks or structures favorable to a geothermal reservoir existed at depths of 6,000 feet (1,829 meters), 2) there were many dikes in the rift zone; they could be located at any depth below the dike

complex, and 3) there was a possibility of a geothermal reservoir in the interdike compartments below 4,000 feet (1,220 meters).(17)

The issue was resolved in a series of meetings and discussions among the project director and the program coordinators. It was decided that since there was enough money for only one deep drill, it would be counterproductive to stop just when the most difficult portions of the well had been completed.

Completing the drilling

In early April 1976, after the production casing was installed to a depth of 2,200 feet (671 meters), the drilling proceeded rapidly. By April 27, the well was drilled to its target depth of 6,400 feet (1,951 meters). The final 4,200 feet (1,200 meters) of the well had been bored in less than three weeks, with no difficulties or significant problems. Since the drilling mud at 6,000 feet (1,829 meters) was about 145°F (63°C) and heating up as time passed, it was known that the well was hot. However, it was not known how hot the well was or whether it was productive.

The first measurements, the well logs, were conducted in late April, after the well had been drilled to its target depth. WRI used its own Gearhart-Owen equipment and hired an operator to conduct neutron, gamma, self-potential, and resistivity logs; these logs would provide indications of the formation's permeability and porosity. Temperature logs were also taken; they indicated that at a depth of 4,000 feet (1,220 meters), the well temperature exceeded 300°F (135°C), the upper limit of the equipment. Thus, precise temperatures were unknown, but it was certain that the temperatures were favorable.

The contractor then conducted a cement-bond log. This log would determine the integrity of the concrete used to cement the casing. Any flaws in the concrete would have to be corrected before completing the well. The cement-bond log indicated a lack of bond, and by implication, gaps in the cementing, from 40 to 220 feet (12 to 67 meters) and from 320 to 868 feet (97 to 264 meters).

Following the well logging, an HGP staff meeting was held and it was determined that three tasks would have to be undertaken. First, the gaps in the cementing of the casing would have to be filled or the well's steam pressure and thermal stresses could severely damage the casing. The gaps would have to be filled before proceeding further. Second, a slotted liner – a 7 5/8-inch (18-centimeter) diameter steel tube with 8 slots per foot (0.3 meters) – would have to be run into the well from a depth of 2,200 feet (670 meters) to a depth of 6,400 feet (1,951 meters). The slotted liner was essential. It would prevent the well's bottom uncased section from caving in, and its 2-inch-by-3/4-inch (5-centimeter-by-1.9-centimeter) slots would allow steam or hot water to enter the tube from the side and be transported to the surface. Third, the drilling completion tests would have to be conducted.

These three tasks would require funds above and beyond HGP's budget, since all funds had already been used to complete the drilling.

It was estimated that the three tasks would require an additional \$248,000. The project director therefore again contacted ERDA officials, and they invited him to present a progress report of the drilling at a meeting of the ERDA geothermal coordinating group in late April. At the meeting the progress of the drilling was reviewed and requests were made for additional funds to complete the well and to conduct the well testing. Additional funds were then promised to the project and the director returned to Hawaii and ordered 4,500 feet (1,373 meters) of slotted liner. Arrangements were also made to remedy the gaps in the casing.

Later in the month ERDA officials formally notified HGP that they were releasing \$85,000 immediately and would release an additional \$175,000 as soon as it could be transferred from the central office in Washington. They also mentioned that they would provide an additional \$300,000 in 1977 to comprehensively test the well.

Completing the well

After the money was secured in early May 1976, Gearhart-Owen perforating equipment and personnel were contracted to fill the gaps in the casing. Also purchased were the valves, gauges, and drilling rig time necessary to install the slotted liner and complete the wellhead plumbing. Finally, the project director arranged for KRTA to continue as consultants and he released funds to purchase testing equipment such as separators and sampling bottles.

The special equipment and operators necessary to fill the voids in the cementing were not available until late May, so work on the well was halted for three weeks. Then, in late May, the special personnel and equipment arrived and the correcting of the casing gaps began. In a four-day period, the special operators perforated the cement with controlled explosive charges, and then forced cement through the perforations into the cementing gaps. The contractor then ran a cement-bond log and determined that the gaps were filled.

In early June, the slotted liner was inserted into the well without any problems. The contractor first used water to cool the hot mud, which had hardened in the bottom of the well, and then obtained circulation. Next the bottom sections of the well were reamed out and the slotted liner was run into the well from 2,200 to 6,400 feet (671 to 1,951 meters). After the liner was installed, the mud in the liner was flushed out, and the well head plumbing including the side and master valves were installed.

While WRI was completing the well in June, the HGP project staff, aided by KRTA, conducted the drilling completion tests. HGP project staff, directed by Bill Chen, a professor of engineering at the University of Hawaii at Hilo, first did a survey of the well's baseline temperatures. Temperature at 4,000 feet (1,219 meters) was about 338°F (170°C); between 4,400 to 6,000 feet (1,341 to 1,829 meters) it remained constant, ranging between 464° and 482°F (240° and 250°C); and below 6,000 feet (1,829 meters), the temperature exceeded 500°F

(260°C). Subsequent temperature surveys, conducted before and after the water pumpdown tests, indicated that the well was continually getting hotter as more and more of the drilling and mud cuttings were cleared from the liner. On June 15, eight days after the second pumpdown tests, the temperature at 4,000 feet (1,219 meters) was nearly 572°F (300°C); and at 6,400 feet (1,951 meters) the temperature exceeded 608°F (320°C).

The other significant completion test was the water-loss or pumpdown test, indicating the level of permeability. To conduct this test, HGP researchers pumped water into the well at rates of 0, 100 (380), 200 (760), and 300 gallons (1,140 liters) per minute, and simultaneously measured the back pressure with a Kuster pressure gauge. If the pressure increased over 150 psi, it would indicate a very poor permeability and nonproducing well.

The initial measurements indicated that the rise in pressure when pumping water into the well between 0 to 300 gallons (1,140 liters) per minute exceeded 700 psi. More pumpdown tests were conducted because the high back pressure could have been created by drilling mud or cuttings obstructing the slotted liner and preventing the inflow of geothermal fluid. However, subsequent tests also indicated high rises in pressure and relatively impermeable conditions (see table 3.5).

Following these tests, WRI demobilized its part of HGP. Employees cleaned the site, removed excess material, removed drilling equipment, and dismantled the rig. However, the most dramatic aspect of the drilling completion test still remained to be done – starting the well.

On June 22, members of HGP's engineering program, who would conduct the output tests, attempted to start the well by airlifting. A hose attached to an air compressor was inserted into the well and the compressor was started. The compressed air then evacuated upper layers of cold liquid to lighten the well's liquid column and to allow it to be heated by the hot geothermal fluid and steam at the bottom. The first attempts to start the well were unsuccessful. Finally on July 2, 1976, the well was flashed and allowed to flow for five minutes.

With the initial flashing of the well, the drilling completion tests were concluded. However, HGP would still have to conduct the formal well tests to determine the well's potential and productivity.

The Testing Period

The testing period of the HGP-A well lasted from July 1976 to June 1978 and was funded by the Energy Research and Development Administration (ERDA), which in 1977 was consolidated into the national Department of Energy (DOE), and the state of Hawaii.(18) The total funds awarded to HGP amounted to \$439,000 during this time period.

Organization of the Hawaii Geothermal Project in July 1976

The top priority during this period was, of course, the well testing and each of the programs was redirected to reflect this priority. The

Table 3.5. Summary of Pumpdown Test

<u>Date</u>	<u>GPM*</u>	<u>Time of Flow (minutes)</u>	<u>Volume (gal)</u>	<u>Back Pressure (psig)</u>
June 6	340	46	15,640	700
June 6	108	105	11,340	500
June 6	108	60	6,480	500
June 6	200	55	11,000	600
June 6	300	70	21,000	700
June 6	530	10	5,300	750
June 6	630	7	4,410	800
June 6	300	8	2,400	700
June 6	200	5	1,000	600
June 6	100	6	600	500
June 7	300	3	900	—
June 7	100	180	<u>18,000</u>	300
Total			98,070 gal	

*Gallons per minute.

Source: Hawaii Geothermal Project, HGP-A Reservoir Engineering, September, 1978, p. 7.

project director, although still responsible for the overall management, coordination and leadership of HGP, now increasingly concentrated on policy, planning, and strategy for future geothermal development in Hawaii. The HGP executive committee would also continue to play a large role in policy making for the future.

The engineering program, assigned the responsibility of conducting the well tests, became the most visible, as well as the most heavily funded, program. Consistent with previous policy, Paul Yuen, the engineering program director, had responsibility for allocating funds and making substantive program decisions. Bill Chen would be at the site to supervise the tests.

The geophysics program was consolidated into a geoscience program. Researchers of the new program would not only synthesize the

geological, geophysical, and geochemical surveys into an integrated interpretation, but also would oversee all new scientific inquiries, such as environmental monitoring and the measuring of physical samples from the well tests. The change in program designation thus reflected the program's broader and more encompassing scope. Named as coordinator of the new program was Charles Helsley. Helsley was a professor of geology and geophysics and was also the newly recruited director of the Hawaii Institute of Geophysics. Because he had worked previously with other deep drills, it was believed that he had the knowledge and experience necessary to synthesize all the geological and geophysical data into an integrated interpretation. This was particularly important since there had been many conflicting interpretations and none was completely consistent with the actual findings from the drilling.

The environmental/socioeconomic program was nearing completion of its research activities, and would be phased out by Robert Kamins, the director, after two crucial reports were finished. These reports were: 1) an environmental baseline study of the Puna area, and 2) an assessment of geothermal development in Puna. Kamins expected both reports to be completed by January 1977.

Initiating the output well tests

In July 1976, after the well had stabilized, the engineering program researchers prepared to conduct the output tests to determine the well's potential productivity and life span. As described by KRTA in the testing program, the well would be allowed to discharge continuously for extended periods, during which the temperature, volume, pressure, and chemical content of the discharge would be measured. After the discharge period, the well would be shut down, and over the next few weeks researchers would record the well's temperature and pressure at various depths. If well temperature and pressure recovered rapidly, it would indicate a potentially large reservoir.

The first extended discharge test was scheduled for July 22. Since a good deal of public enthusiasm and attention was now focused on the project, it was planned to be a four-hour public display. In this regard, HGP had been primarily a research project with no real tangible product to capture the imagination. But now, there was more than an exciting idea: the Hawaii Geothermal Project could actually display, for the first time in Hawaii, human-controlled geothermal energy. The public display was dramatic and impressive. Flowing continuously for four hours, the well sent geysers of steam and liquid over a hundred feet into the air. Because no muffling or silencer was installed for the first test, the noise exceeded 122 decibels – the sound of a 747 at takeoff.

The test results themselves were very promising and even exceeded the expectations of the KRTA consultants. Lip temperature exceeded 302°F (150°C) for the entire four hours while lip pressure from the 6-inch (15-centimeter) discharge pipe was 23 psig at the end of four

hours. Subsequent temperature surveys indicated that the well recovered in about seven days and that the major production zones occurred between 3,500 (1,067) and 4,500 feet (1,372 meters) and at 6,400 feet (1,951 meters).

Based on the test results, the engineering program researchers were able to make some tentative conclusions. First, based on the data, they deduced that the well had a mass flow rate of 166,000 pounds per hour – assuming an enthalpy of 800 Btu/lb and 15 percent efficiency, the well could generate 5 MW of electricity. They also noted that fluid and steam were flowing naturally into the slotted liner, indicating that there was greater permeability than they had assumed from the water-loss tests. Longer tests, however, would have to be conducted before any conclusions could be made about the well's productivity.

Before conducting such tests, however, the engineering researchers would have to construct more elaborate testing equipment. Thus, over the summer of 1976, the researchers added to the well a silencer-separator to muffle the loud noise of the discharge and to separate the water from the steam. Also added to the well were a twin cyclone sampler, which would obtain gas and water samples for chemical analysis, and a calorimeter to measure specific enthalpy. Figure 3.12 illustrates these instruments on the well.

Extended flow tests: problems and progress

In November 1977, with the new instruments and equipment installed, HGP researchers conducted a two-week test flow. The tests were extremely encouraging and demonstrated that the well was capable of discharging continuously for a two-week period. Most prominently, well output stabilized after 25 hours. HGP researchers collected other data, such as noise level, temperature, steam quality, and water and gas samples; and they calculated the enthalpy of the discharge and its thermal power. (See "Phase 4: Evaluation and Refinement" for complete data.) By the end of 25 hours of continuous discharge, thermal power had stabilized to about 22 MW and at the end of the test it was still at 20 MW. Thus, from the perspective of demonstrating the well's generating power, the November tests were a success.

However, since the tests were, for the first time, being conducted under real world conditions, they also introduced a new issue – the well's impact and interrelationship with the human community in Puna. This issue was underscored by the land use near the well. North and south of the well were undeveloped areas covered by recent lava flows and sparse vegetation. But to the east and west there were homes. Twelve families lived within one mile of the well and within two miles there were several residential tracts that were being developed. The largest of the residential tracts was Leilani Estates, with a total of 2,146 house lots.(19) Although, at that time, only 50 families were living in Leilani Estates, they had formed an active community association that represented 2,036 of the owners of the lots.(20) Two other residential tracts nearby included Lanipuna Gardens and Nanaweale

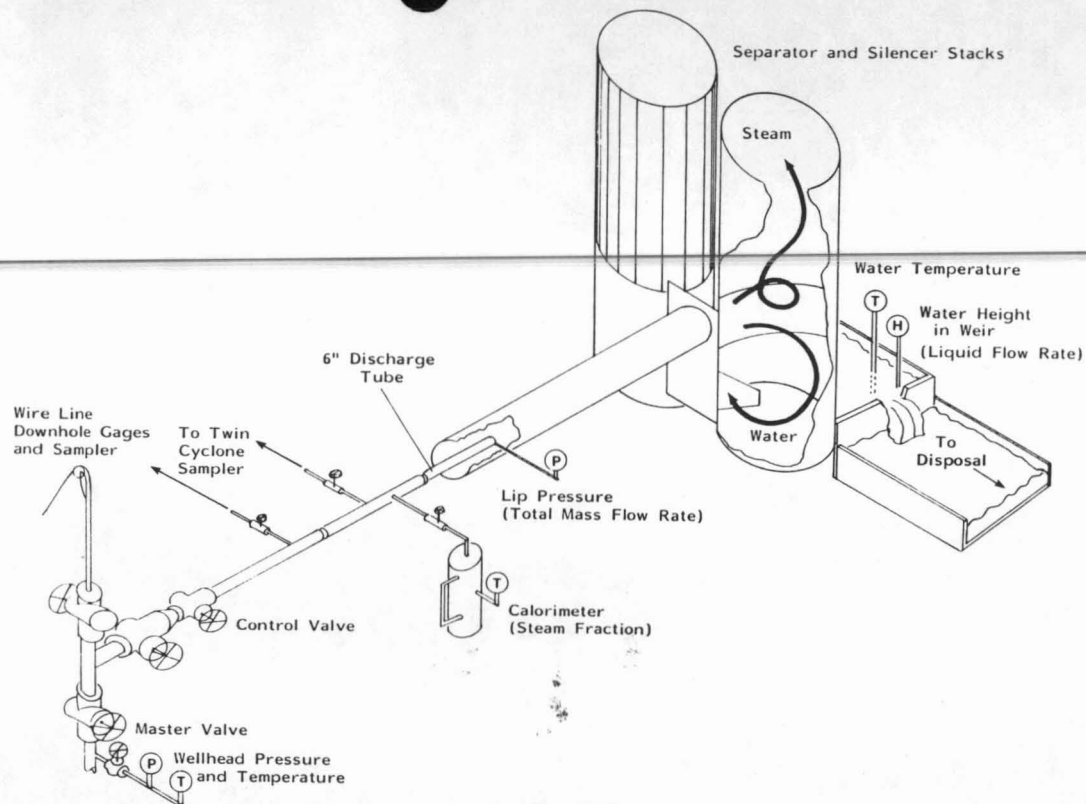


Fig. 3.12. HGP-A well-head testing equipment.

Estates; both had few actual residents but both were being planned for development. Within the immediate vicinity of the well there is also a state park and one paved road, with usually very light traffic (see fig. 3.13). A statement from the environmental baseline study gives one an idea of the setting:

In most hours of most days, the quiet of the roads in this portion of the Puna District is not much disturbed by passenger cars, or by an occasional truck or bus, most of them traversing the distance to beaches on the Puna Coast. (The well drilling itself generated a fair amount of traffic, not only from the dozen members of the drill crew and scientist observers, but also from some tour buses, whose operators were glad to find a drilling rig to add to the attractions of tourism in this outstandingly quiet corner of the Island of Hawaii).(21)

Further from the well site, but within a several mile radius, are the communities of Pahoehoe, Kapoho, Opihikao, Kalapana, and Kaipu. Many of the residents of these communities are native Hawaiians, who have lived in Puna for generations and who have adopted a rural agricultural life-style. The entire district of Puna, in fact, is predominantly rural and agricultural. There are extensive cultivated fields of sugar cane and papaya, with smaller areas utilized for growing guavas, oranges, and macadamia nuts. Additionally, there are several small family enterprises growing tropical plants, such as anthuriums and orchids. Interspersed between the villages and the low-density residential tracts are areas of lush tropical vegetation, conservation zones, and several forest reserves (see fig. 3.14). In sum, the Puna district maintains a somewhat traditional rural Hawaiian setting. It is sparsely populated, little developed, primarily agricultural, and outstandingly quiet.

In this setting, the November flow tests began. And, within a few days, the Leilani Community Association objected vigorously to the noise from the well's discharge. The well had been muffled since the July test, which created a noise of 122 decibels, but even with the muffler, the sound at the roadside was 87 decibels, while one mile away the noise was projected to be 70 decibels and at two miles, 40 decibels. The Environmental Protection Agency (EPA) recommended 55 decibels as a tolerable daytime level for residential areas, but the well discharged continuously and within an extremely quiet surrounding. Thus, the community association contacted their city council representative and also contacted state officials, demanding that the tests be halted. One resident stated that the noise was intolerable; he described the sound as a "bloodcurdling banshee howl." Other residents pointed out that the area was outstandingly quiet and that many of them had moved to the area for just that reason. Moreover, their whole way of life was being disrupted by the nuisance of the noise. The county officials responded that they would try to help. But, after investigating the problem, they discovered that there were no noise standards governing residential areas on Hawaii. Thus, the county officials called HGP and asked them to confer with the residents of the area.

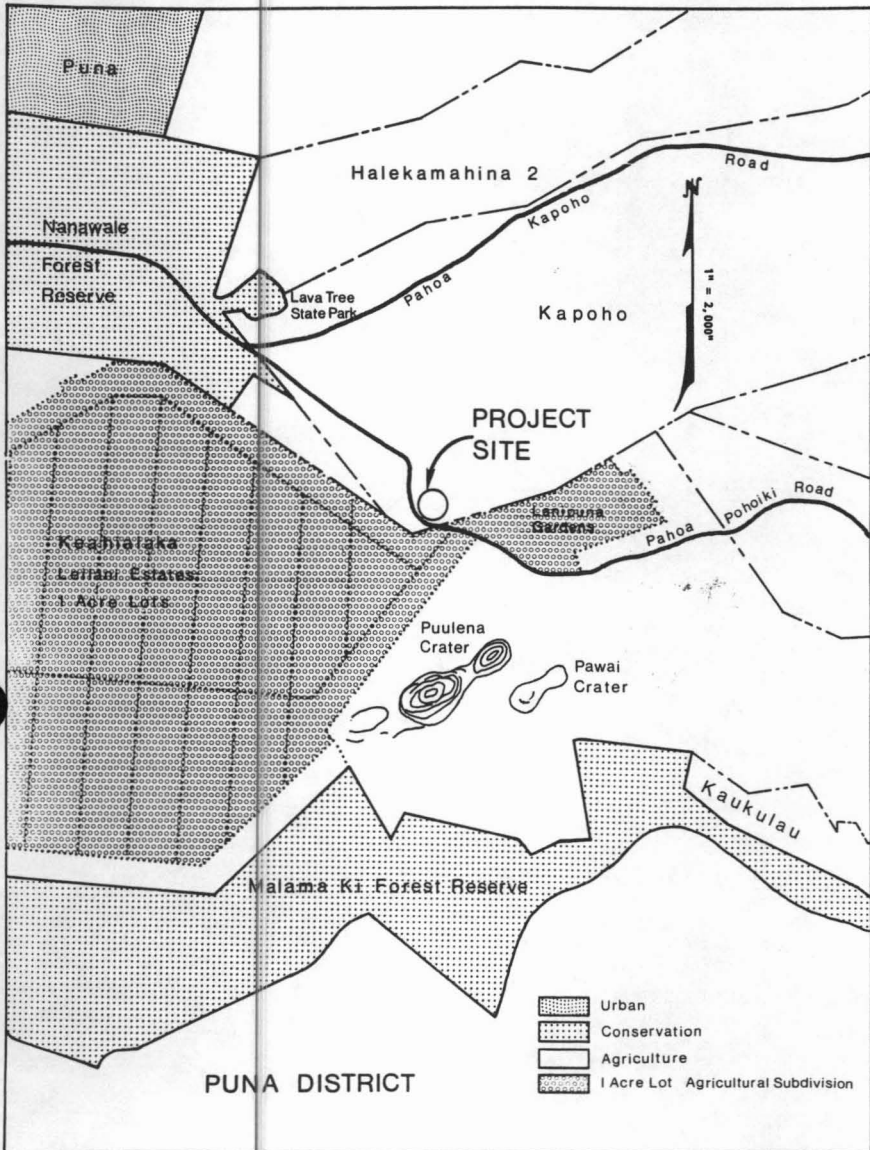


Fig. 3.13. Land use within the immediate vicinity of HGP-A.

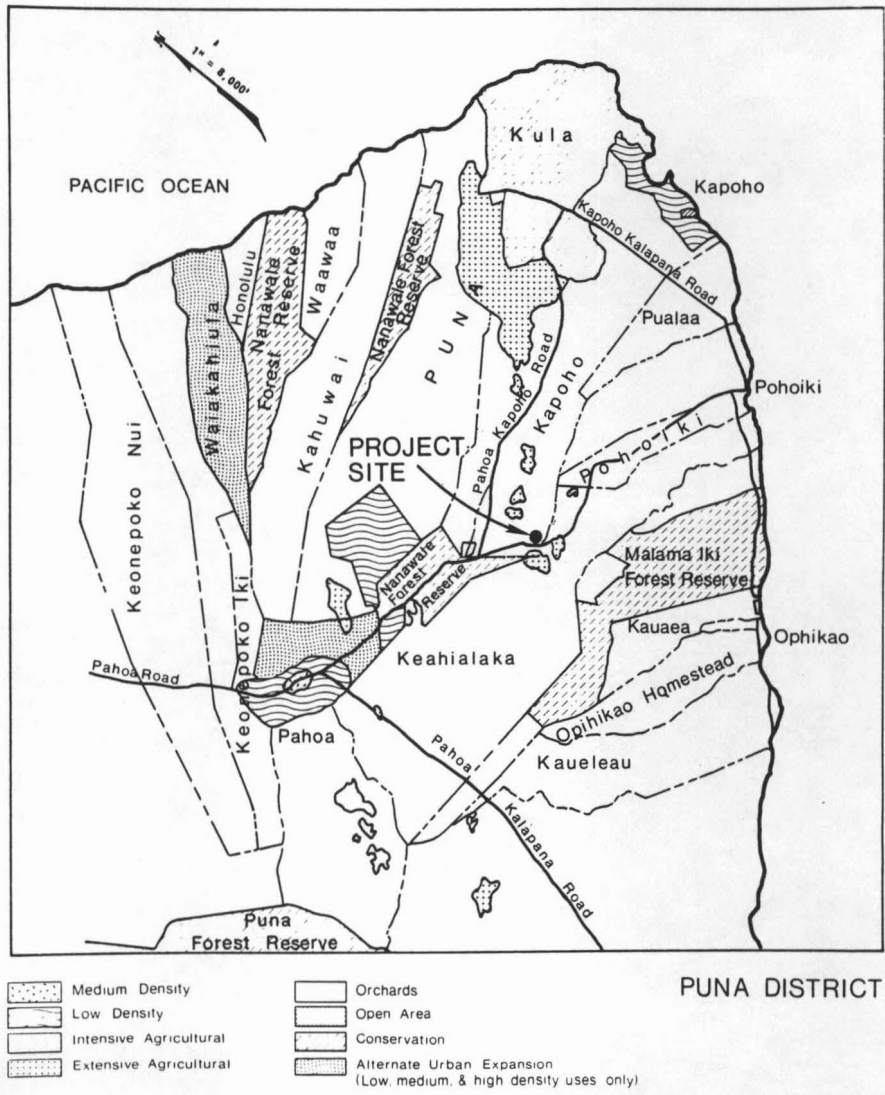


Fig. 3.14. Puna district.

Eventually, the project director met with the residents and agreed to try and improve the muffling on the well. He pointed out, however, that the well was experimental and that the tests would be a nuisance for only a limited time. To further cooperate with the residents, Bill Chen, who lived on the island and was helping oversee the tests, agreed to confer with them before tests and to meet with them when they wanted.

Well tests in December and January 1977

In December, the engineering program researchers conducted a flow test to obtain downhole temperature and pressure measurements while the well was discharging. The tests revealed that downhole temperatures approached 662°F (350°C), one of the highest temperatures ever recorded in a geothermal well. Also encouraging were measurements showing that the well's temperature, pressure, and mass flow rate had increased significantly since the November test.

During the December tests, residents again strenuously objected to the noise. Thus additional muffling was put on the well. This satisfied the residents, and they agreed to a two-week test in January 1977.

The January 1977 tests were intended to determine the well's potential generating capacity using different diameter orifice plates. This would allow HGP researchers to determine which orifice was the optimum size to be used for generating electricity. The results of the test appear in table 3.6.

Well tests, March to May 1977

Following the January tests, Paul Yuen and Bill Chen decided that the well should be tested for a 90-day period to collect enough data to project the well's electrical generating capacity over a 30-year period. The test began on March 21, with the discharge line fully open. A few days later a 3-inch (7.6-centimeter) orifice was placed into the line since this was probably the discharge diameter that would be used to generate electricity.

Soon after the discharges began, residents of nearby Pahoa, Nanaweale Estates, and Leilani Estates objected vigorously to the well's odor. The odor was caused by hydrogen sulfide, which was emitted into the air during discharge. In large amounts, it is lethal; in small amounts, it is obnoxious. It has the smell of rotten eggs and the human nose is extremely sensitive to its odor – able to detect it in quantities as small as three parts per billion. The residents thus registered complaints with the Hawaii County Council, the state Department of Health, and directly to the project director. Some residents complained that the hydrogen sulfide fumes were environmentally dangerous and that the odor was a health hazard. Other residents complained of respiratory problems, while a doctor blamed the fumes for causing increased incidences of sinus difficulties, asthma, bronchitis, diarrhea, and dermatitis.

Table 3.6. Throttled Flow Data for January 26-February 10, 1977

<u>Orifice Size (Inches)</u>	<u>Total Mass Flow Rate (klb/hr)*</u>	<u>Steam Flow Rate (klb/hr)</u>	<u>Steam Quality (Percent)**</u>	<u>Wellhead Pressure (psig)</u>	<u>Wellhead Temp. (°F)</u>	<u>Possible Electrical Power Output (Mwe)</u>
8	101	64	64	51	295	3.3
6	99	65	66	54	300	3.4
4	93	57	64	100	338	3.5
3	89	54	60	165	372	3.5
2 ½	84	48	57	237	401	3.3
2	81	43	53	293	419	3.1
1 ¾	76	39	52	375	439	3.0

*klb = 1,000 pounds

**Steam quality = fraction of steam in total flow

Source: Hawaii Geothermal Project, April 1, 1977, p. 19.

A Department of Health representative met with the residents and explained that there were no ambient air quality regulations for hydrogen sulfide; there were, however, federal regulations for industry which specified ten parts per million over an eight-hour day. The HGP well was discharging about three parts per million. The Department of Health official thus explained that the odor was a nuisance that would have to be controlled, but that he could not force HGP to do anything.

After residents protested a while longer, the project director met with the Leilani Community Association. At the meeting, he emphasized that the well was still experimental and that this was probably the last time any extended tests would be conducted before HGP installed scrubbers to virtually eliminate odor. He also noted that natural volcanic eruptions were intensifying the fumes. However, he did acknowledge the nuisance factor and he agreed that if there was any indication of a health hazard he would stop the test immediately. In response the residents cited numerous health problems and indicated that their water supply was largely from a rain catchment system and therefore any fumes in the air were likely to endanger their water. After discussing the problems further, it was agreed to shorten the test period.

The test period was shortened to 42 days and ended on May 9. Although the full 90-day flow test would have provided considerably more information, the engineering program researchers had sufficient data to make some tentative conclusions about the electrical potential of the well. The most promising aspect of the data was that the well output had stabilized and thus extrapolations indicated that the well could continue to generate 3.0 megawatts of electricity over a 30-year period. (See "Phase 4: Evaluation and Refinement" for complete well test results.)

Completion and Handover

Policy and direction of HGP, 1976-1978

While the engineering program team was conducting the well tests during 1976 and 1977, John Shupe and other members of HGP were formulating plans, policies, and strategies for promoting Hawaii's geothermal energy development. In order to begin the planning activities, Shupe, during the middle of 1976, discussed with ERDA officials the possibility of their funding a long-term, large-scale geothermal program in the state of Hawaii. He discovered that ERDA would be reluctant to support any such program for the following reasons:

1. ERDA was doubtful that Hawaii's geothermal energy development had relevance and significance for the nation as a whole. In this respect, HGP had emphasized the importance of obtaining geothermal knowledge of island volcanic regimes, but had never emphasized the potential national spin-offs of such research. If Hawaii was

to continue to receive federal funds, a strong case would have to be made for Hawaii's contribution to the nation's geothermal energy development.

2. Since ERDA was a national federal agency, there was concern that the concentration of support – over \$2,000,000 thus far – to one specific geographical location was unbalanced. Requests for support of geothermal projects had been received from over 100 different locations and many would not be funded if Hawaii received a disproportionately large share of the national budget.
3. Finally, ERDA was skeptical about funding development projects through universities because ERDA's objectives were application and utilization. The more practical and effective approach, which was normally ERDA policy, was to fund projects through industry and other "real world" organizations, such as utility companies and energy-related corporations.

Since ERDA funding was essential to future geothermal development efforts, Shupe prepared a number of recommendations that addressed these concerns. For the immediate future, he had two suggestions. First, he recommended that HGP be dissolved at the end of 1977, following the completion of the final research reports. However, an essential corollary to HGP's dissolution would be the formation of a geothermal development consortium, composed of the State of Hawaii, the County of Hawaii, the University of Hawaii, and the Hawaii Electric Light Company (HELCO). Second, he recommended that the consortium plan and implement a coordinated program of geothermal research and development for the state, with its first objective being the construction and operation of a small demonstration plant, powered by the HGP-A well. These two recommendations were intended not only to satisfy ERDA's policy of funding "real world" projects, but also to achieve HGP's ultimate goal of generating geothermal electricity on a practical scale.

These two recommendations required immediate and vigorous action. Thus, in late 1976, Shupe asked Hideto Kono, the state energy resources coordinator, to assume the lead role in organizing and directing a geothermal consortium. Kono agreed and he formally contacted officials from the Hawaiian Electric Company, and from Hawaii County. The state and county governments and the electric company were already cooperating in the development of geothermal power through their active participation in HGP. These groups thus agreed to participate in the consortium, viewing it as a natural outgrowth of the cooperative effort in HGP and as the appropriate organizational entity for developing Hawaii's geothermal power. Also included in the consortium was the University of Hawaii, represented by HGP.

Formally organized in early 1977, the consortium was named the HGP-A- Development Group (HGP-A D/G). Kono was selected as the group's executive director and Shupe was authorized to negotiate for the group in any dealings with ERDA. The members of HGP-A D/G held

several meetings during the early part of 1977 and they agreed that their immediate goal was to build a geothermal power facility to demonstrate the feasibility of generating geothermal energy from the HGP-A well. To achieve this goal, the group first prepared a funding proposal for ERDA. Each consortium group contributed its special expertise and the state government provided the funds to contract TRW, Inc., a geothermal consulting firm, to aid in preparing the proposal. Completed in April 1977, the proposal was submitted to ERDA.

HGP-A D/G proposal to ERDA: general design of experimental station

The proposal requested funds to build an experimental geothermal facility at the site of the HGP well. The facility was envisioned to include three basic components: 1) the power generation system, 2) the experimental system, and 3) the support system.

The first component, the power generation system, was to be composed of a turbine generator, condensor, cooling power, antipollution devices, electrical conversion and distribution apparatus, and either percolation ponds or a reinjection well. It was envisioned that the steam and the hot fluid from the well would be piped directly to a separator where they would be separated. The hot fluid would then be piped to the reinjection well or to percolation ponds for disposal, while the steam would be routed to a demister. The demister would remove any remaining moisture in the steam and then allow the dry steam to exit into the turbine at 52 klb/hr at 160 psig. This would produce 3 MW of electricity.

The electricity would go to a specially constructed substation and then be fed into HELCO's power grid. However, since the grid at the substation could accept only 2 MW of electricity, the 1 MW surplus would either be fed into a load bank where it would be dissipated, or it would be used to supply the facility's electrical needs. Power plant operations were to be handled in a motor control and instrumentation center where the turbine regulator, the voltage regulator, voltmeters, ammeters, pressure meters, and other process control instruments would be contained.

The plant was intended to operate in an environmentally sound manner. The steam used to run the turbine was to be exhausted into a condensor, where cool water would condense the steam, leaving water for noncondensable gases. The gas would flow to a cooling tower and, after being cooled, it would either be piped to the reinjection well or recirculated to the condensor. The noncondensable gases, primarily hydrogen sulfide, would be treated in a pollution abatement system and, when safe, released into the atmosphere.

The second component of the facility was to be the experimental system, which was to consist of three test pads, one to conduct electrical geothermal experiments and two to conduct nonelectrical experiments. It was envisioned that nonelectrical experiments could include testing the environmental effects of geothermal fluid, devel-

oping a heat exchanger, and developing methods for sampling fluids and gases. The electrical experiments could include testing small geothermal generators, developing a total flow turbine, and evaluating corrosion and scaling problems.

The third component of the facility, the support system, was to include the supply buildings, the administration offices, the repair and maintenance areas, the buildings for the power station, the electrical substation, the instrumentation and equipment needed to monitor the facility, the electrical lighting, and all access and service roads. A detailed layout of all three components would later be integrated into a final design.

Management plan

The proposal called for three stages of activity. The first stage was to be the overall planning; specific activities were to include devising a system of project management, drawing up a preliminary budget and a work schedule, and establishing a monitoring program to control activities. Also during this period, an environmental impact statement would be completed and a design contractor would be selected to draw up specifications for items such as the turbine generator and pollution control apparatus. The design contractor was then to integrate the power system, the research system, and the support system into the design for the total facility.

The second stage was to be the construction stage. During this stage the management was to evaluate the bids and to select an implementation contractor, who would handle all aspects of the construction. The contractor would be responsible for all subcontracting and for ensuring that construction meet design criteria.

The final stage was to be the operation and training phase. The plant would be operated by HELCO, which would contribute the time of a geothermal engineer to train a staff of technicians and power operators. After the facility was completed, the staff would operate the station and HELCO would purchase the electricity at the commercial price. In the proposal, it was estimated that the plant would have a yearly income of \$260,000, which was enough to pay for all operational expenses plus leave a sizeable surplus.

Cost estimates of the proposal

Four cost options were included in the proposal. 1) The first option, costing \$6,447,000, was for the basic facility as described, using the most modern equipment. 2) The second option, costing \$5,189,000, was for the basic facility, but using a surplus Westinghouse turbine generator adapted to geothermal requirements. 3) The third option assumed the use of the surplus generator and also deleted the reinjection well from the basic facility. It was estimated to cost \$4,655,000. 4) The final option assumed the use of the surplus generator, and deleted both the reinjection well and the research facilities. Summary of the costs for each option is in table 3.7.

Table 3.7. Hawaii Geothermal Research Test Facility
Estimated Plant Equipment Costs
(in Thousands of Dollars)

	<u>Item</u>	I	II	III	IV
1.	Turbogenerator	1,162.0	200.0	200.0	200.0
2a.	Substation	445.7	445.7	445.7	445.7
2b.	Instrumentation	126.2	126.2	126.2	126.2
2c.	Load bank	54.6	54.6	54.6	54.6
3.	Cooling water circulation system	54.3	54.3	54.3	54.3
4.	Steam separator	71.3	71.3	71.3	71.3
5.	Demister	16.0	16.0	16.0	16.0
6.	Hydrogen sulfide abatement	150.0	150.0	150.0	150.0
7.	Reinjection equipment	43.8	43.8	10.0	10.0
8.	Trailers (2)	61.9	61.9	61.9	61.9
9.	Condenser/eductors	61.5	61.5	61.5	61.5
10.	Cooling tower	87.5	87.5	87.5	87.5
11.	Site preparation	309.2	309.2	309.2	222.2
12.	Foundations	128.4	128.4	128.4	105.0
13.	Field piping	353.3	353.3	312.1	189.0
14.	Remote instrumentation				
15.	Injection well	428.7	428.7	107.6	107.6
16.	Research facility	866.7	866.7	866.7	0
17.	Miscellaneous	226.6	177.3	156.9	100.6
	Design costs	689	684	666	544
	Construction costs	1111	869	770	493
Total		6447	5189	4655	3100

Source: HGP-A Development Group, Proposal for a Geothermal Electric and Nonelectric Research Facility Utilizing the HGP-A Well on the Island of Hawaii, vol. 2 appendix A.

Project completion

While the consortium was negotiating with ERDA during 1977, HGP continued with its own project responsibilities, which increasingly centered upon the analysis of the data and the completion of final research reports. The environmental/socioeconomic program was the first to complete its research, formally concluding operations in January 1977 with the publication of a prototype environmental impact statement (EIS), entitled "An Assessment of Geothermal Development in Puna, Hawaii." Although the assessment was not represented as an EIS, it did contain much of the information that would be required in a formal statement. It contained, for example, the environmental baseline measures of the chemicals in the Puna area's air, water, and soil. It also described the plants and animals indigenous to the area, noting especially the rare and endangered species. Further included in the assessment was a discussion of the socioeconomic conditions in Puna, including the residents' employment pattern, the housing situation, the life-style, and the distribution of the population. Finally, the assessment compared potential benefits of geothermal development – such as implementation of an alternative form of energy, creation of more jobs in the area, and utilization of an indigenous source of energy – with potential costs, such as the transformation of agriculturally zoned land to industrial land, an increase in the noise level, and an increase in the amount of airborne pollutants. Overall, it was estimated that the benefits of geothermal development were substantially greater than the costs.

As previously described, the engineering team completed the well testing in May 1977. During the remainder of 1977, the engineering team members analyzed the test results and then, in 1978, published a summary reservoir engineering report.

Researchers in the geosciences program continued to analyze data from the earlier geophysical surveys and completed two new research tasks. In January 1977, the researchers conducted seismic refraction surveys, and in June 1977, they completed preliminary geochemical and hydrological analyses of the samples from the well flow tests. During the rest of the year, analysis of all geophysical and geochemical data continued, and attempts were made to integrate all data into a unified interpretation. Although the synthesis could not be accomplished during 1977, several research reports were sent to the Department of Energy in 1978 to summarize the geosciences work. These summaries included reports of all the geothermal explorations conducted from 1973 to 1977, including the electrical, magnetic, gravity, geochemical, seismic, and photogeologic surveys.

The initial plan had been to phase out HGP upon the submission of the research reports. However, the future of HGP depended upon the HGP-A Development Group proposal submitted to ERDA in April 1977. ERDA itself was being reorganized into the United States Department of Energy (DOE) during 1977, and after the transition was completed, a decision would be made. ERDA formally became the DOE in October

1977 and in November DOE officials notified the development group that DOE would fund the proposal. Specific details of the proposal would have to be worked out in negotiations with DOE.

Regardless of the future of HGP, the responsibility for the development of geothermal energy in Hawaii was now transferred to the HGP-A D/G, which was the entity that would accomplish HGP's ultimate goal of utilizing geothermal energy in Hawaii.

PHASE 4: EVALUATION AND REFINEMENT

No formal evaluation of the Hawaii Geothermal Project was conducted. This was because HGP was successfully integrated into the HGP-A Development Group and therefore became a part of the overall effort to develop geothermal power in Hawaii. From this perspective, the project is ongoing and cannot be evaluated independently of the larger development effort which has yet to be completed. In this section, then, a summary of the major results of the HGP between 1973 and 1978 will be presented.

Well test results

From the standpoint of accomplishing the implicit goal of discovering an exploitable geothermal resource, HGP proved to be a successful project. The HGP-A well was discovered to be one of the hottest geothermal wells in the world, with downhole temperature reaching 676°F (358°C). See figure 3.15 for a temperature profile of the well. There was a natural two-phase flow into the well bore with quality geothermal fluid and a substantial total flow rate. (See table 3.8 for a complete statistical profile.)

Table 3.8. HGP-A Discharge Results

	<u>November</u>	<u>December</u>	<u>January</u>	<u>March</u>
Well-head pressure (psig)	47	53	59	59
Well-head temperature (°C)	146	150	151	153
Mass flow rate (klb/hr)	88	103	114	120
Steam flow rate (klb/hr)	60	64	72	75
Steam quality* (percent)	68	62	63	62
Electric power potential (mWe)	3.4	3.8	4.3	4.5

*steam fraction.

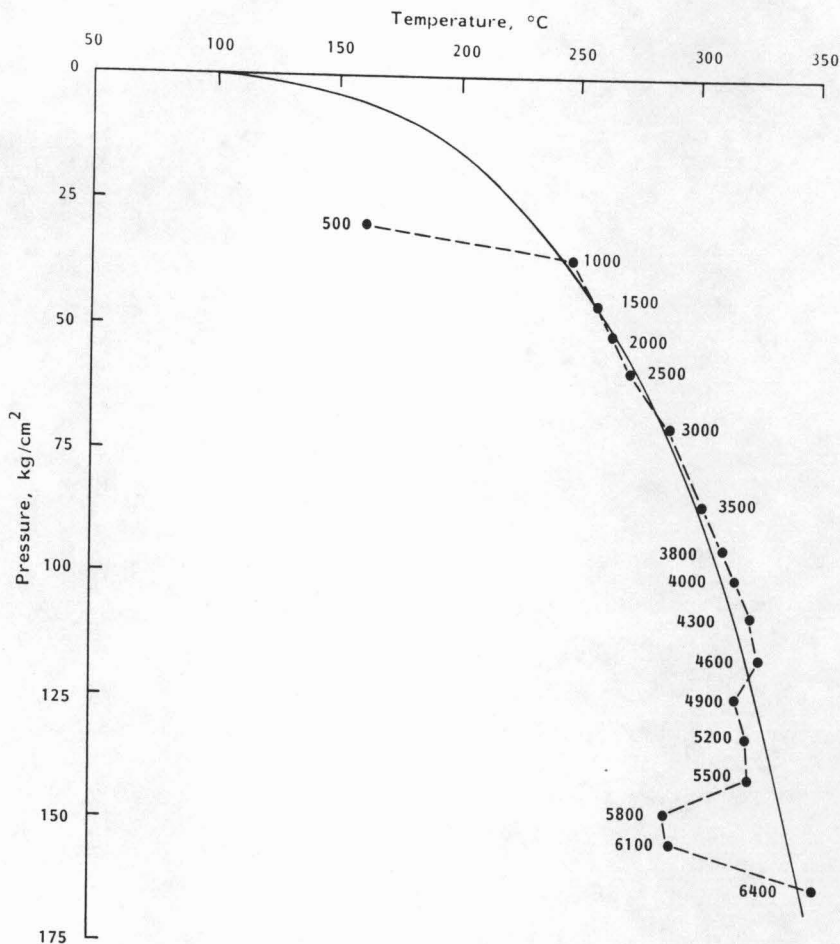


Fig. 3.15. Temperature profile of HGP-A well.

Based on the data collected from the well tests, it was estimated that HGP-A could generate 3 MW of electricity for a 30-year period. Table 3.9 shows the power projections for the well. It was also estimated that the entire reservoir feeding the well could be substantially larger. Estimates of the reservoir's generating capacity ranged up to 500 MW of electricity for the next 100 years. Compared to the island of Hawaii's total need of about 90 MW of electrical capacity and the state of Hawaii's present electrical capacity of 1400 MW, this was quite substantial. However, estimates based on a single well were not sufficient to accurately predict the capacity of the geothermal reservoir; it would be necessary to drill other wells for more information.

Table 3.9. Long-range Power Projections for HGP-A

Time in Years	Total Mass Flow Rate in klb/hr	Steam Flow in klb/hr	Well-head Pressure in psig	Enthalpy in Btu/lb	Power in MWe
1	81	59	153	900	3.2
15	78	58	142	904	3.0
30	77	57	140	906	3.0

Source: Hawaii Geothermal Project, HGP-A Reservoir Engineering, September, 1978, p. 42.

Geological results

Geologists and geochemists analyzed the cores and cuttings collected during drilling and found that the rock formation was tholeiitic basalt which could be divided into three zones of alteration (see table 3.10). Zone 1 where the alteration began, occurred between 2,220-4,265 feet (673-1,300 meters) and was characterized by montmorillonite, with minor calcite, quartz and chlorite. Zone 2 occurred between 4,455-6,250 feet (1,350-1,894 meters), with the principal alteration mineral being chlorite and accessories being quartz, actinolite, and montmorillonite. The boundary temperature between zones 1 and 2 was about 617°F (325°C). The third zone became dominant from about 6,234 feet (1,900 meters) to the bottom of the well. Actinolite predominated in this zone with chlorite, quartz, pyrite, and hematite secondary. The boundary temperature between zones 2 and 3 was 644°F (340°C).

From the top of the well to a depth of about 3,500 feet (1,067 meters) the lava was highly permeable, with excellent permeability between 2,500-3,000 feet (762-914 meters). Then, from about 3,500-6,200 feet (1,067-1,890 meters), the permeability became poor, although layers of medium permeability existed throughout the dike making possible geothermal production. At the bottom of the well, from 6,200-6,600 feet (1,890-2,012 meters), the permeability was excellent. Figure 3.16 illustrates the zones of permeability as they relate to the HGP well.

Based on this information, the HGP researchers derived several speculative models of the well's underground system. One of the most probable models depicted two production zones, one at about 4,400 feet (1,341 meters) and the other at about 6,400 feet (1,951 meters). Both zones were supplied by aquifers that were recharged by rainfall percolating into the ground. However, only high levels of rainfall could penetrate to these zones because of the alternating layers of poor permeability. The heat at these depths was sufficient to boil the water and produce steam.

Table 3.10. Geologic Analysis and Interpretation of Possible Production Zones

Depth from Well-head (feet)	Microscopic Analysis	Megascopic Analysis	Boundary Temperature Zones of Alteration
0			
500	Unfilled	Generally high permeability	Little or no alteration
1,000	Unfilled		
1,500	Unfilled		
2,000			
2,500	Partially Filled		
3,000	Partially Filled	Higher Permeability	Zone 1 Major mineral: montmorillonite Minor minerals: chlorite, quartz, calcite
3,500	Filled	Generally low permeability, but possibility for layers of medium permeability	
4,000			
4,500	Filled		320°C
5,000			
5,500	Filled	Varying but generally low permeability	Zone 2 Major mineral: chlorite Minor minerals: quartz, actinolite, montmorillonite.
6,000	Filled		340°C
6,500	Partially filled	High permeability	Zone 3 Major mineral: actinolite Minor minerals: chlorite, quartz, pyrite, hemitite

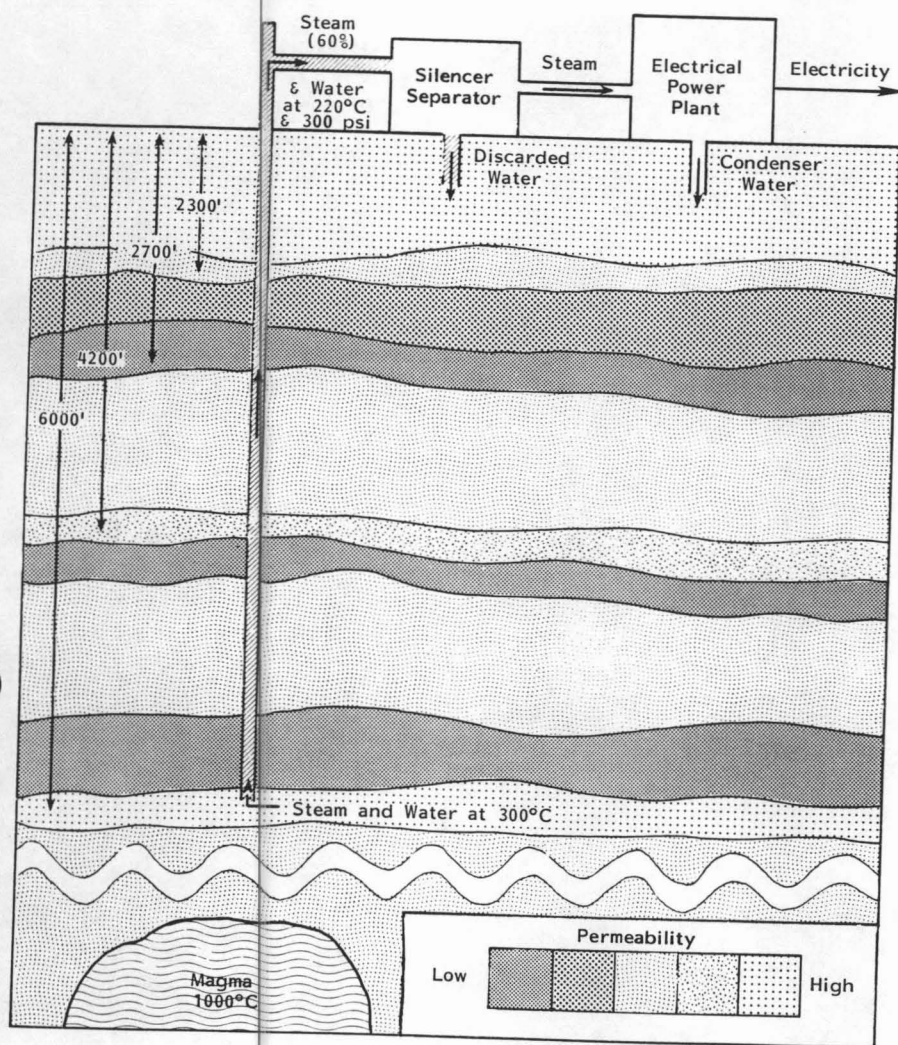


Fig. 3.16. Layers of permeability as related to HGP-A.

Well emissions

During the well testing, the HGP researchers collected atmospheric samples to determine the airborne chemicals emitted from the geothermal discharge, and they collected downhole samples to analyze the chemicals in the geothermal fluid. With respect to airborne emissions, there was concern about sulfur dioxide, hydrogen sulfide, and mercury. Both sulfur dioxide and hydrogen sulfide were bothersome, but the levels were never dangerous. In fact, their levels in the atmosphere did not change during the well tests, thus indicating that the well was not adding significantly to the natural volcanic emissions of sulfide into the atmosphere (see table 3.11). However, the odor of hydrogen sulfide is particularly offensive to humans; it smells like rotten eggs. Moreover, it can be detected in quantities as small as 3 parts per billion. Thus, although the flashing of the well did not significantly increase the atmospheric levels of hydrogen sulfide, it did disturb nearby residents. This was especially true when there was no wind or when the prevailing wind blew toward nearby homes. The last bit of odor would have to be eliminated before further developments could take place.

Table 3.11. Aerometric Data for HGP

<u>Date</u>	<u>Well Status</u>	<u>Sulfur Dioxide*</u>	<u>Hydrogen Sulfide*</u>	<u>Mercury**</u>
May 1975	Predrilling	0.5	0.5	1.1
May 1975	Predrilling	0.5	0.2	1.2
July 1976	Flashing	0.5	0.2	9.9
Nov. 1976	Well shutdown	—	—	0.1
July-Aug. 1977	Well shutdown	0.3	0.2	0.8

*Parts per million.

**Microgram per cubic meter.

Source: Adopted from, Revised Environmental Impact Statement for the Hawaii Geothermal Research Station Utilizing the HGP-A Well at Puna, Island of Hawaii.

Levels of mercury were another matter. Mercury is potentially dangerous at any level and the provisional federal standard is not more than 0.1 microgram per cubic meter for continuous exposure. Mercury levels near the drill site were high, and during the July 1976 flashing, mercury levels rose to 9.9 micrograms per cubic meter. Later analysis, however, revealed that the area naturally contained high levels of atmospheric mercury. Moreover, the high levels recorded in July were caused not by the well testing, but by volcanic vents. Table 3.11

illustrates that even with the well shut, mercury in the air sometimes exceeded 0.1 micrograms per cubic meter. After monitoring the air for two years, researchers could find no evidence of a buildup of mercury.

The chemical content of the geothermal fluid was a cause of concern because any geothermal plant would have to dispose of or reinject the used geothermal fluid back into the earth. This could contaminate the ground water. However, the chemical content of the HGP geothermal fluid did not differ significantly from that of the brackish water wells in the area (see table 3.12). This suggested that the area's ground water had been naturally contaminated due to the upward movement of heated salt water and that no Ghyben-Herzberg lens – a pool of fresh water floating on salt water – existed in the area. Only one potential hazard existed, silica. Because of the high downhole temperature, the level of silica in the HGP fluid was 440 milligrams per liter, several times higher than normal. It would have to be filtered out before the well's geothermal fluid could be reinjected into the ground.

Table 3.12. Comparison of Chemical Content of HGP-A
with Nearby Wells and Springs
(Milligram/Liter)

<u>Site</u>	<u>Chlorine</u>	<u>Calcium</u>	<u>Potassium</u>	<u>Magnesium</u>	<u>Sodium</u>	<u>Silicon Dioxide</u>
HGP fluid (downhole)	925.0	84.2	135.0	2.1	830.0	440.0
Isaac Hole Spring	3,534.0	32.4	86.0	200.0	2,020.0	81.5
Airstrip Well	303.5	23.0	13.6	28.0	238.0	71.3
Allison Well	281.0	13.4	10.8	15.0	216.0	24.1
Malama Ri Well	3,811.0	66.8	109.0	210.0	2,105.0	81.5
Rain water	7.2	0.25	0.25	0.75	4.5	0.0

Source: Adopted from Hawaii Geothermal Project, Environmental Baseline Study for Geothermal Development in Puna, Hawaii, September 1976; and Hydrology and Geochemistry of Hawaiian Geothermal System: HGP-A.

Noise

Despite constant improvements in the muffling of the well, noise continued to annoy residents throughout the testing period. Although the noise did not exceed Environmental Protection Agency standards

when measured at nearby houses, it was high pitched and thus irritating. Moreover, many residents were accustomed to the quiet of the rural area, while others had moved to Puna specifically to get away from the loud noise. Table 3.13 provides data on the noise. Thus any subsequent developments would have to eliminate the noise problem.

Table 3.13. Level of Noise near Well Site
(in Decibels)

Location	7/19/76 (without Silencers)	11/3/76	1/27/78	2/10/77 (3-Inch Orifice)	5/7/77 (3-Inch Orifice)
Corners of well					
40 feet away	113	100	96	98	—
40 feet away	113	98	93	95	91
70 feet away	94	98	89	91	—
70 feet away	94	98	91	91	89
At roadside, 100 feet away	122	87	80	80	75
Estimated					
1 mile away	—	—	—	—	70
2 miles away	—	—	—	—	49

However, HGP was only an experimental program; the demonstration plant had not been built. When electricity was actually generated, the sound would be muffled by the generator, into which the steam would be fed, and by the building, which would house the generator and the operating facilities. It was anticipated that this would reduce the noise to an acceptable level.

Economic aspects of the project

The Hawaii Geothermal Project was from the beginning a cooperative effort among the federal, state, and county governments, the utility companies, and the University of Hawaii. Each contributed by giving the project expert advice and by providing services when appropriate. In addition, each group supported the project financially. During the years 1973 to 1978, HGP's total allocation amounted to \$3,387,000. Table 3.14 illustrates the total funds granted to the project during this period.

Although this total amount was large, it must be put into perspective. First, the total was spent over a period of five years, and it

Table 3.14. Financial Summary for HGP, 1973-1978
(in Thousands of Dollars)

<u>Funding Entity</u>	<u>1973</u>	<u>1974</u>	<u>1975</u>	<u>1976</u>	<u>1977</u>	<u>1978</u>	<u>Total</u>
National Science Foundation	269	200					469
Energy Research and Development Administration/Department of Energy (1977)			119	1472	270	147	2,008
State of Hawaii	100		500		66		666
County of Hawaii	100						100
Water Resources International				60			60
Hawaiian Electric			45				45
Other			<u>39</u>				39
Totals	469	200	703	1,532	336	147	3,387

funded numerous activities ranging from geophysical surveys to socio-economic assessments. Second, the project was intended to provide the basic research and development that would lead to the exploitation of geothermal resources in Hawaii. It was intended neither to be an exploration for geothermal resources nor to be an eventual profit-making venture. Finally, the project did discover a productive geothermal well and a potentially large geothermal reservoir. It is this well and potential reservoir that the 3.5-MW demonstration plant will utilize.

EPILOGUE

In June 1978, negotiations between the Department of Energy and the HGP-A/DG were completed and a four-year well-head generator contract was signed providing \$6,268,256 of local and federal support. An additional agreement was reached with the utility company, which would purchase an estimated \$482,758 of electricity generated by the well during the initial two-year period of operation. Design of the generator system is nearing completion, and the facility will begin supplying electricity to the residents of Hawaii in early 1981.

NOTES

- (1) City and County of Honolulu, Report of the Mayor's Energy Resources Committee, 1973, p. 1.
- (2) Robert M. Kamins, An Assessment of Geothermal Development in Puna, Hawaii, Hawaii Geothermal Project, January 1977, pp. 4-5.
- (3) Department of Planning and Economic Development, State of Hawaii, "Energy Use in Hawaii," in The Role of Alternate Energy Resources in Promoting Island Self-Sufficiency, Hearings before the Subcommittee on Energy Research and Development, (Washington, D.C.: U.S. Government Printing Office, 1979), pp. 110-111.
- (4) Kamins, An Assessment of Geothermal Development, p. 5.
- (5) Center for Engineering Research, University of Hawaii, A Proposal to the Hawaii State Legislature in Response to House Resolution 351 Requesting a Study of New Energy Sources for the State of Hawaii, 1971, p. 7.
- (6) Honolulu Star-Bulletin, March 5, 1973, p. A-20.
- (7) Hawaii Geothermal Project, Summary Report for Phase I, May 1975, p. 27.
- (8) Honolulu Advertiser, February 9, 1974.
- (9) A.S. Furumoto, G.A. Macdonald, M. Druecker, and P.F. Fan, Preliminary Studies for Geothermal Exploration in Hawaii, 1973-1975, December 1977, Hawaii Institute of Geophysics, University of Hawaii, p. 14.
- (10) Hawaii Geothermal Project, Phase II Revision to Proposal AER7500285-000, December 1974, pp. 2-51.
- (11) Ibid., pp. 5-6.
- (12) Hawaii Geothermal Project, Summary Report for Phase I, p. 27.
- (13) Kingston Reynolds Thom and Allardice Limited, Hawaii Geothermal Project Testing Program, August 1975, pp. 1-2.
- (14) Kingston Reynolds Thom and Allardice Limited, Hawaii Geothermal Project Drilling Plan, p. 2.
- (15) Entry in the drilling log of the Hawaii Geothermal Project, n.d.
- (16) Personal communication from John Shupe.

(17) Personal communication from John Shupe.

(18) It was decided that if the well was successful it would be named in honor of Agatin Abbott, the initial drilling program coordinator, who died on July 31, 1975. Hence the "A" in HGP-A stands for Abbott.

(19) Honolulu Advertiser, April 22, 1977, B1.

(20) Ibid., B1.

(21) Hawaii Geothermal Project, Environmental Baseline Study for Geothermal Development in Puna, Hawaii, September 1976, pp. 5-7.